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Naval communications systems

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NAVAL COMMUNICATIONS SYSTEMS

A Thesis

By

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Dean of the Naval Postgraduate School

Table of Contents

LIST OF ILLUSTRATIONS

Figure

NAVAL COMMUNICATIONS SYSTEMS

ABSTRACT. This paper attempts to determine the requirements of communication systems in general, and naval communications specifically. Unlike commercial communications, naval system design must solve the problem of extreme speed without the loss of reliability, and extreme flexibility without overcomplicating operation or increasing physical bulk. A comparison is drawn between present naval communication practice and systems which are practically attainable if the potentialities of the communication art are fully exploited. Although the field selected for this paper is so broad that it is discussed, for the most part, in general terms, some phases are treated in detail to illustrate the manner in which seemingly unimportant detail affects overall system design. The fundamental truths and relationships are emphasized, for they then serve as a point of departure into the more complicated relations of system details. Finally, the design requirements of a practical inter-ship naval communication system are discussed and a solution offered as an example of system design. The problem of communication security, and the many special systems for obtaining security, is purposely not discussed.

NAVAL COMMUNICATIONS SYSTEMS

I GENERAL

1. Background

Radio was but ten years of age when the United States became involved in the First World War. In 1907 U.S. Patent 841387 was obtained by Lee deForest and the vacuum tube, which had been merely a laboratory toy of some interest, became the powerful tool which in forty years was to cause a revolution in every field of human activity. By 1917 the infant radio had cut its teeth in disaster at sea and the electron art was emerging as a full fledged science in its own right, with the continuing development and application of physical theory to the design of equipment. In that year, trans-oceanic telephony and radio broadcasting were being played with on an experimental basis, but for the most part radiotelegraphy was well intrenched in commercial and military practice, and the "brass pounder" ruled the radio wavelengths.

In the two decades intervening between the First World War and the outbreak of the Second World War, radio communications matured and expanded with the full force of mass research by the commercial communications laboratories, employing hundreds and thousands of individual

specialists, each contributing his small share to the total understanding. As the art expanded, the role of the individual in this expansion became smaller and more specialized following the well established pattern of the growth of scientific knowledge. The early experimenters were versatile fathers to their growing child, serving alike as designer, builder, and operator. It was still possible for one mind to encompass completely and understand the then limited field of radio and electronics. With growth, however, the functions of research, design, and operation became separated among groups of special interest and the operating functions became, in general, divided from the design function, with the operating interests determining the pattern of development.

The operator is concerned, not with things, but with methods and the economic implications of those methods. Under the compulsion of these economic considerations, and under the guidance of the operating groups, commercial communications have increased in efficiency by exploiting new technical developments and putting them to work economically in transporting intelligence from place to place. The old fashioned telegrapher has disappeared from commercial communication practice, being replaced by the automatic telegraphers, -- the

automatic Morse systems, and the teleprinter. The new art of voice transmission has created systems operationally simpler than telegraphy, the radio-telephone, of which radio broadcasting is a branch. The even newer arts of television and facsimile have yet to prove themselves economically in wide scale operation, being in many respects yet in the experimental and developmental stage. At every level in the rise of commercial communications, new proposals have been made and subjected to the most searching examination from the operating viewpoint, for regardless of the ingenuity of the technical design, the new proposals must compete with other systems on an economic basis.

2. Present Naval Practice

There is no need to belabor the obvious. It is widely known that, commercially, radio communications have had a continuous record of progress and increased efficiency through the economic exploitation of the advances of physical research from the days of deForest's patent. It has been mentioned here only to provide a self evident contrast with naval communications.

In the Second World War, though technical advancements had been made in materiel far beyond that of World War I, the technique of handling traffic had not advanced

space to utilize fully the new capacities developed in commercial practice during the intervening years. The fleet radio circuits were manned in World War I by the old professional telegrapher. World War II recruited the amateurs, the "hams", to man the code circuits. The telegrapher has now disappeared and the amateur is turning to the more exciting realm of phone. There is no longer any group in the United States that remains well versed and interested in telegraphy to serve as a pool of trained communication personnel if we persist in handling fleet traffic by manual code. There are clearly but two alternatives. The Navy can embark upon a program of system modernization designed to simplify operations, or it can prepare to train personnel in outmoded and difficult operational techniques for the next emergency. The former will allow us to train a few groups in simple system practices; the second will require us to train large numbers in complicated procedures and mechanical operations.

Although the shore communication systems have been modernized by the employment of commercial equipment and techniques, the sea going equipment has seen little improvement, systematically, since the first days of radio. The day of mechanization has yet to come, and the great bulk of traffic is still handled by manual labor.

Fleet communications pose a problem peculiar to itself and unlike any met in commercial practice. The problem is not so much one of scale, but of complexity. Commercial communications involve, for the most part, point to point circuitry with subsidiary switching problems to achieve flexibility. Fleet communications circuits are largely multi-point conference circuits, inherently more complicated than point to point. In addition, fleet circuits must be provided by radio, rather than wire, because of the water borne, mobile nature of the stations, and radio in itself imposes restrictions upon systems design not encountered in the equivalent wire circuits.

The speed of a communications system is measured, not alone in words-per-minute of transmission, but also in the elapsed time from originator to addressee. The true test of system speed must include time lost in preparation before transmission and processing after reception. Any time during which the message lies idle in the channel from sender to receiver must be charged as undue delay to be eliminated. The best system will have a uniform rate of traffic flow over its entire length, and traffic will not pile up in the bottle neck of a slow traffic link.

In present practice, the greatest delays do not

occur between the sending key and the receiving headphone, for even moderate sending speeds are usually sufficient to clear waiting traffic on most fleet circuits. The greatest delays occur before transmission and after reception. No real attempt has been made to extend the communication system to include the province of internal message handling before and after transmission as an element of the technical design problem for communications equipment. It has not been sufficiently recognized that the communication system is a man-machine combination, and, in any such system, the machine must be designed to comply with the limitations of the human element. In the early days of radio, the capabilities of the man were superior to the machine he operated and the human limitations were not evident. The demands of modern naval communications are greater than the human operator can handle, and the machine has been developed technically to the point where it can handle traffic much faster than the man. It is now time to design the machine to relieve the load on the human and thus increase the over all speed of the system.

The operational steps in the communication channel are set forth in Figure 1. Actual systems may be more elaborate, but no system can have fewer operations without some sacrifice to performance. The present province

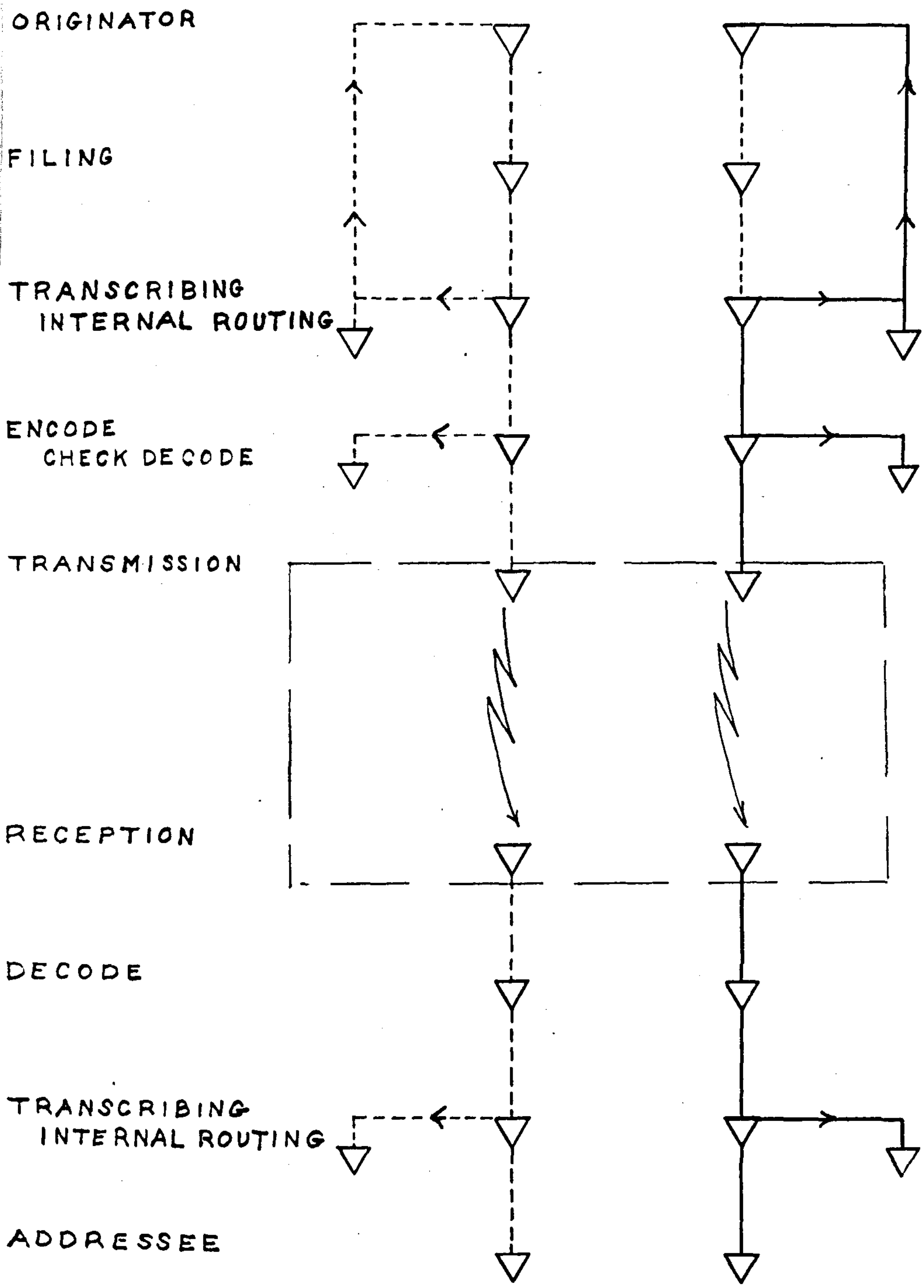


Fig. 1 Basic Message Handling.

---- Manual Transfer

—— Electrical Transfer

▽ Operation Performed

of system design is that which concerns transmission and reception, the operations within the dotted rectangle. The left hand diagram represents the present chain of message handling. The message leaves the originator and enters the communication system for filing, transcribing, and internal distribution. The movement from one operation to the next is manual. Each operation represents a fairly specialized function requiring personnel devoting their entire attention to that operation and subject to the possibility of ever prevalent human error. The operation of encoding and check decoding entails the greatest delay and opportunity for error because of its complexity.

At no point in this chain, after the message leaves the originator, is there any operation that cannot be performed automatically by electronic or mechanical machinery, and performed faster and more accurately. The installation of such equipment would serve the triple function of eliminating human error, improving the system speed by electrical operation and distribution, and, incidentally, eliminating thereby the need for a large staff of highly trained operating personnel. The right hand line diagram shows that, although none of the basic steps are eliminated, most of the operations can be mechanized and interconnected electrically.

3. Possibilities of Modernization

The teleprinter was developed commercially to replace the telegrapher and the manual message handling problem which he entailed. The input motivation required for the teleprinter is particularly adapted to the human operator. There is no unusual problem presented by the teleprinter that cannot be mastered by the ordinary stenographer, or yeoman, in a very short time. In fact, a person completely inexperienced as to typing technique can still operate the teleprinter faster than most telegraphers can clear traffic with the Morse key. The output is in the form of electrical telegraphic impulses which automatically actuate all similar machines connected on the same wire or radio link. Therein lies the greatest virtue of the teleprinter; the ability to make a positive, direct record of the intelligence being transmitted or received in many different stations at once, making at the same time a number of copies for internal distribution. This eliminates the redundant operations of transcribing and manual distribution. In addition, the teleprinter lends itself admirably to the mechanical transpositions and substitutions required for machine coding and decoding which further permits the elimination of the redundant motions involved in coding and check decoding. And lastly, the intelligence from

one teleprinter may be recorded for automatic retransmission or relay.

It is readily evident that there is much to be gained by mechanization of the communication system. In every branch of engineering it is well known that the human element of a machine-man combination is the weakest and most susceptible to error when performing repetitious or monotonous operations. Present naval practice requires personnel to spend many hours performing operations of duplication and monotonous repetition. The reception of the Morse radio signals is a subjective recording operation and must operate through a human link with the attendant susceptibility to error from fatigue. After recording, the message goes through several subsequent stages of transcription in decoding and internal distribution. And at no stage are the operations performed in a positive, non-subjective manner which eliminates the chance of human error.

The degree of human error present in any operation is a function of experience, complexity of the operation, the physical and mental condition of the human link, and environment. Experience is not a controllable factor in wartime, for the press of mobilization will not always allow adequate training of personnel in the many exacting

duties of communications. Some operations lend themselves nicely to human manipulation, while others are mechanically or psychically difficult for the human body to perform. These factors are partially controllable if the system is designed with consideration for the adaptability to the human machine (and this providing that the human machine can be analyzed sufficiently accurately as to its best modes of operation.) The physical and mental condition of the human machine is an almost uncontrollable factor, for it is subject to many variable influences. Likewise, the environment is only partially controllable, for it is secondary to many other considerations, particularly on shipboard.

It is evident, though, that if a mechanical or electrical system can be substituted for the very fallible human, many of the problems of procurement, training, and system error which the human element engenders, can be eliminated. The design and procurement of the necessary complicated equipment, and the training of competent personnel to service and maintain that equipment, does pose a separate problem, but a problem that can be solved in the leisure of peacetime operations, and not under the press of national mobilization. It is probable that any future war will develop so rapidly as to preclude the opportunity to develop a competent communication

personnel, and the training cannot be accomplished successfully in peacetime. It is imperative that a program of survey and modernization be undertaken now, when time is not of the essence, rather than to wait until a time of national crisis when it will become apparent that our present concepts of systems design are too hopelessly inadequate and antiquated to cope with the rapid fire developments of modern warfare.

The electrical system is designed within the framework of natural laws, and these laws are, unlike the laws of human behavior, constant and knowable. Consequently the machine system can be exactly controlled and varied to meet the requirements of the particular service, and made independent of undesirable factors. Such a system will be invariant, not only with widely varying operating conditions, but also with time. Communications represents a basic social relationship which is independent of any special equipment used. The very basic concept of communications is to get intelligence from one person in one place to other persons in other places through channels designed to overcome intervening obstacles. It is immaterial to the intelligence how these channels are established as long as they are capable of handling the intelligence and overcoming the obstacles. If these channels are once established, it

should then be possible to alter the component design of the system elements, without the necessity of altering the system design, if the end result of the operation remains unaltered. Referring again to Figure 1, it is evident that the component equipment at any single point of operation may be altered if the function of the equipment remains unchanged. A basic system can be built up, designed for the special requirements of the naval service, which is invariant, but will allow for expansion and modernization without in any way affecting the basic manner of operation. This is predicated upon the premise that the basic system is designed according to the needs of the service and within the limitations of the natural laws of engineering. It is first necessary to determine the requirements of the service, and then to determine the natural technical limitations to fulfilling these requirements.

II COMMUNICATIONS SYSTEMS

1. Naval Communications

It has been mentioned that one of the distinguishing features of naval communications is multiplicity. The originator seldom addresses his communication to one single activity, nor is the same message of the same degree of importance to all addressees. That which is highly important to one party may be of only inform-

ative interest to another. Also messages do not all have equal importance in their impact on the naval establishment. It is necessary that the various classes and levels of traffic be defined and classified according to the structure of the navy itself.

The exercise of effective naval command is dependent upon two factors; efficient organization and efficient communications. The naval commander obviously cannot hope to accomplish his task unless the forces under his command are efficiently organized and deployed towards that end. It is also clearly apparent that he cannot accomplish his task if he is unable to communicate his will to his command. The first aim of communications is to serve naval command, and must always be subordinated to this purpose.

Command is not the only function of the naval commander. Problems subordinate to his basic command problem are the complementary freedom of action problems involving security, logistics, training, intelligence, and communications itself. All of these problems must be solved by the commander himself, and they cannot be implemented unless he can make his decisions known, not only within his command, but to all the coordinate and superior organizations with whom he must coordinate his decisions and actions. Thus logistics require the in-

terchange of information between the commander and the logistic agencies upon which he is dependent. Intelligence requires channels of communications from the intelligence source to the commander. Communications involves the commander in complementary details of traffic handling and procedures within the limitations of the system equipment provided to him. The better the equipment with which he is to work, the better and more effective will be his handling of the other problems in furthering his strategic or tactical aims.

The communication requirements of a particular freedom of action sphere do not remain static, but vary with the nature of the operations which the commander undertakes. It is therefore impractical to classify messages according to the operational functions of command, but it is rather necessary to classify them as to (1) the administrative and operational organization of command, and (2) the operational import of the message itself.

The five complementary functions of a naval commander are subordinate to his command function, but situations often arise wherein the subordinate problems are of greater operational importance than any pending command problems. A message to a fleet unit at sea

directing it to obtain fuel and supplies at a certain base is a logistic order with operational importance outweighing the particular operations underway; for the operating units are ever dependent upon their logistic train and cannot long operate without it. But to the logistic agency supplying the fuel, the message is of routine administrative importance.

In general, a division may be made of communication traffic into two categories. Messages that require some action or movement by naval units are classed as operational traffic. Other messages, which require no action of an operational nature, but merely notice of their contents, are classed as administrative traffic. All naval traffic can be classed, with some degree of certainty, into one class or the other. The dividing line is not distinct, however, and the classification is often a question of experience and judgment rather than arbitrary definition. The best test is usually that of the time element. Operational traffic is sometimes defined as messages which require the movement of naval vessels within a specified period of time after receipt. Thus a movement order directing a ship to proceed from one place to another within a few hours after receipt is definitely an operational message, whereas a movement order directing such movement some days in the future

may well be classed as administrative, though it may well become operational as the day specified for the movement approaches. Likewise, a task force commander operating at sea may signal his night maneuvre intentions some hours in advance, and the message could be handled as administrative traffic; but the same orders when issued minutes ahead of execution become operational traffic of the most urgent tactical nature. It is this tendency of messages to change classification with time that makes naval systems design difficult to analyze when determining channel allocations and transmission priority. It is advantageous to segregate administrative and operational traffic for separate handling, but the segregation is at best impermanent and imperfect.

The traffic pattern is but partially determined by the above considerations. The communication channels should follow the command organization, for the normal flow of information and command is from superior to subordinate, with frequent intercourse between coordinate levels of command. The naval establishment is organized with a predominant line structure exercising command vertically through successive echelons expanding downward. There is a collateral horizontal staff function of specializations, such as logistics,

medicine, technical engineering, legal matters, etc. which serve as service adjuncts to the line function. The naval organization is too complex to be dismissed in two lines, though these features are salient. There are vertical lines of administrative responsibility within the staff functions but the interchange of information is carried on through the line function as far as communications systems are concerned, for it is impractical to provide separate channels for the command function and for each of the staff functions.

There is no published study of naval communication traffic as to the organizational pattern with a break down as to relative importance. But even though we cannot make any quantitative conclusions as to the traffic pattern, it is possible to make some general qualitative remarks as to naval traffic.

Traffic usually follows the operational line of command, rather than the administrative line. In peacetime operations, the operational and administrative lines of command usually coincide, but in wartime it is rare that the operational line is the same as the administrative line, for the operating task forces are organized on a functional rather than administrative or type basis. It has been mentioned that administrative traffic is usually not as pressing in time as is opera-

tional traffic, and therefore such traffic is often handled by systems of communication other than radio; i.e. mail, messenger, etc. Thus the communication system will handle operational traffic in a preponderate proportion to the administrative traffic. This places a requirement of flexibility upon the system design, for the operational organization of a naval force is fluid and subject to rapid change.

As to the import of the message itself, messages fall into two classes which have been described as operational and administrative, (applying to the nature of the message itself apart from the command origin). It has been mentioned that the division is usually made on a time basis, so that messages classed as operational are of higher priority in transmission than administrative messages. There is also a difference in the internal message structure. Operational messages are usually short, peremptory commands giving specific instructions or information and requiring definite action or prompt reply in acknowledgement. Administrative messages are usually longer in nature, setting forth ideas in some detail, and not requiring immediate reply. Operational traffic cannot generally wait upon administrative traffic and the two should be kept in separate channels of communications.

There is one other consideration involved in an analysis of system organization. It has been determined that there should be two channels of communications following the chain of operational command. These channels should not extend through the entire chain of command from the highest echelon to the lowest element, for it is undesirable to have all messages delivered to all echelons indiscriminately for two reasons. First, each channel could then handle but one message at a time, and secondly, it may not be desirable, from a privacy and organizational viewpoint, to make all the information contained in all the messages available to all the echelons. On the other hand, it is equally undesirable to transmit messages from a higher echelon to a lower echelon without passing through the intermediate levels of command. The channels, therefore, must not be continuous, but must consist of discrete links which may be joined or disconnected at will to form the particular distribution desired. The manner of connecting these links and controlling them is a technical matter which will be discussed somewhat later. It is sufficient for the present to point out that such an organizational separation can be made on a switching basis to permit the naval commander to establish channels to any part of his command, or to all of it, as desired.

Likewise, channels to coordinate commands can be made integral with the common superior commander so that he is always kept informed of the lateral traffic within the command.

2. Theory of Communications Networks

It is desirable to consider some of the general aspects of the basic technical nature of communications as applied to naval communications before proceeding with detailed consideration of the component details.

Communications is basically intercourse between people by means of words, letters, pictures, etc. to convey ideas or information between individuals or groups. Of the five human senses, only the sense of hearing and the sense of sight are normally employed for communication purposes. Until modern times, communications could only be carried on directly; either vis-a-vis orally or by direct visual signals or messages. These forms of communications might be classed as sensory; that is, detectable by the human senses. But when physical barriers prevent direct sensory communications, resort must be made to some other means of intercourse which are necessarily extra-sensory. Modern technology has provided the extra-sensory communication media by which the physical barriers of distance or

intervening obstacles may be overcome. The sensory matter is translated into the extra-sensory medium, transmitted over all barriers, received and then re-translated into the original sense. A consideration of the available extra-sensory transmission media indicates that the electro-magnetic wave is the most promising of all the possibilities. They may be listed in order of merit.

1. Radio.
2. Metallic wire.
3. Modualted light.
4. Infra-red radiation.
5. Ultra-sonics.

Metallic wire systems are generally not applicable in naval systems as the major link, but are used extensively in shore nets, and as auxiliary circuits on ship board. The three subsequent media suffer handicaps of various degrees which preclude their use as primary systems although they can still be used as adjuncts in special circumstances. Their greatest limitation is that of adequate range, which is the greatest asset of radio as a transmission medium. The remainder of this paper will discuss the technical aspects of radio only as a transmission medium in naval communication systems.

It appears that a communication channel is really a sort of pipeline into which intelligence, in familiar sensory forms, is placed, carried over all the barriers

of space and distance, and delivered to the addressee in the same sensory form in which it was transmitted. It provides, in its highest concept, an extension in space to the radius of normal human intercourse. But practically, and undesirably, it also introduces an extension in time as well; that is, intelligence is delivered, not instantly as in direct intercourse, but after an appreciable delay in time. This delay is not directly attributable to the extra-sensory link itself, but to the processes attendant to preparing that link, preparing the intelligence into special forms required by the particular type of transmission, and upon reception and distribution at the receiving station. In setting the channel up for transmission, contact must be established with the desired addressee, the circuit tested, and procedure agreed upon. Then the message must be filed, transcribed, released, coded, checked, and finally transmitted with similar procedures obtaining at the receiving end.

This distortion in time is not present in direct forms of communications and represents an undesired aberation in the communication channel to be eliminated. It has been pointed out that this aberation occurs, not because of any inherent insufficiency of the extra-sensory portion of the channel, for traffic in this

portion of the channel moves with the speed of light. The delay is caused rather by the mismatch of the channel terminations to the extra-sensory link. There is, so to speak, an "insertion loss" at the points where the extra-sensory (radio) link joins to the human terminal link. This mismatch represents the different capabilities of the two parts of the man-machine combination. The machine is capable of super-human speeds in transmission and performance of complex operations, but the combination must be slowed to a speed consistent with the abilities of the human component. As in any transmission problem, the solution is to remove the mismatch; in this case, to extend the machine portion of the combination to replace the human elements. The channel should extend directly from the originator all the way to the addressee(s).

The next step in the analysis is, then, to examine the technical aspects of extending the machine to this end. Such an extension is not a simple matter for the machine lacks the one major asset of the human, the ability to think and reason. The human can act according to advance knowledge of a situation and according to the reasoned dictates of the particular situation. The machine can only respond to a set of orders <u>after</u> the receipt of the orders, and even then only within the

framework of the designed functions of the machine. For this reason, the machine must be built, in each case, to the particular requirements of the communication system it is to serve. The next sections will deal with the basic building blocks of system design.

III COMMUNICATION CIRCUITS

The rule has been stated that a communication channel should in no way impede the free interchange of intelligence among the several widely separated parties to that channel. Strictly interpreted, this means that the channel must be operated in full duplex with facilities for multipling the connections. As will be seen, such a system is inherently extravagant of equipment and frequency spectrum, and, as a practical matter, it is desirable to approximate this degree of service by systems less extravagant and expensive. The degree to which this approximation may be carried, and still provide a satisfactory system, is a function of the type of service to be carried by the system.

The circuit of Figure 1(a) represents the simplest of all communication circuits. It is essentially a broadcast system wherein all traffic is transmitted "blind" and received by all the parties to the circuit without receipt or acknowledgement. It is easily con-

nected in multiple, and requires little equipment. Its chief disadvantage as a system is that it provides no reverse channel of communication.

The next obvious step is to provide a reverse channel in parallel to the one-way channel and thus form a two-way channel. Figure 1(b) illustrates such a circuit. This is a 4-wire full duplex circuit and is the normal circuit for point-to-point radio circuits in both commercial and military shore installations. Traffic is sent in both directions simultaneously when used for telegraph circuits, or the terminations may be reduced to a 2-wire circuit and used for full duplex telephony. In fleet radio nets, the two-way circuit is more often operated with both channels on the same frequency, for this circuit cannot be operated in multiple without an excessive amount of equipment. The circuit then operates on a half duplex basis but with the possibility of employing break-in procedure. To operate a system in this manner requires a human agency at the terminating ends, for a machine cannot be built with the discriminating qualities of the human ear.

A more exhaustive examination of the drawbacks of a 4-wire circuit is warranted for a radio net is inherently and inescapably a 4-wire system and cannot be

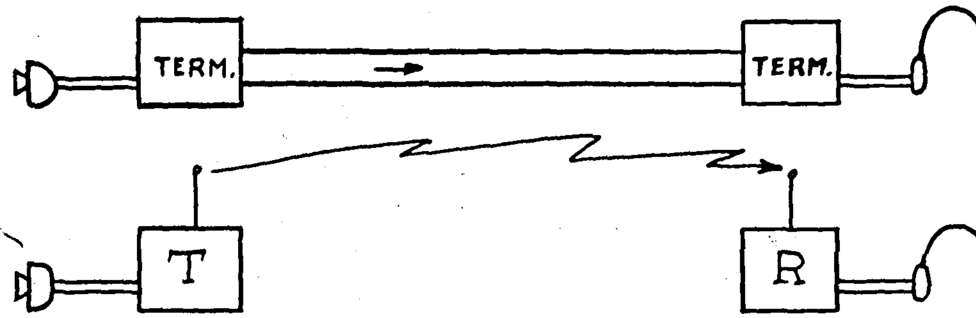


Fig. 1 (a) "One way" Circuit.

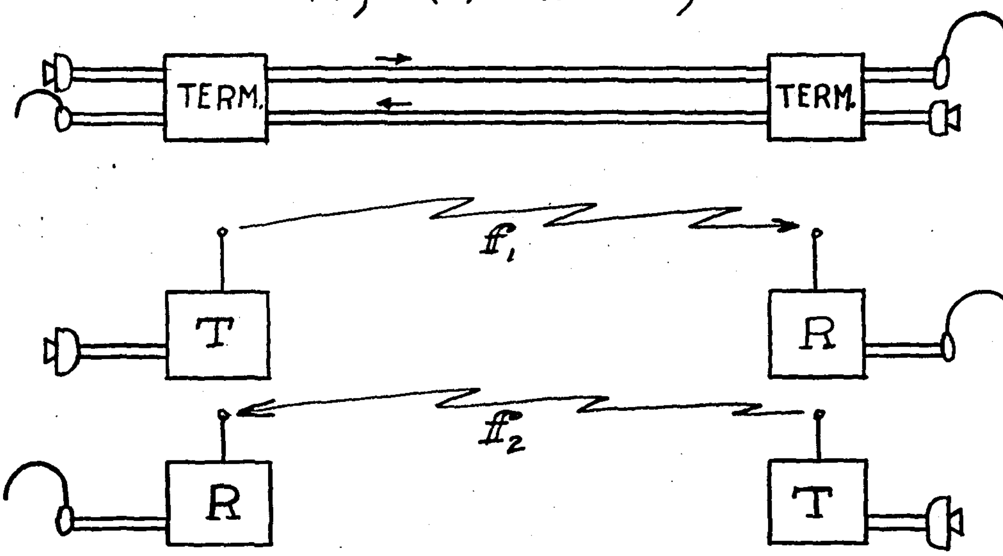
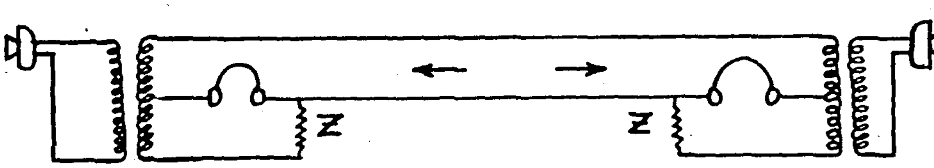


Fig. 1 (b) 4-wire circuit.



NO EQUIVALENT
RADIO CIRCUIT.

Fig. 1 (c) 2-wire circuit.

reduced to a 2-wire circuit by any such means as serve when using metallic wire circuits. Figure 1(c) shows a 2-wire metallic circuit for which there is no equivalent radio circuit. This circuit is not actually used in wire plants for this purpose but represents the basic idea of reduction of a 4-wire circuit to two mettalic conductors. In wire plants, the capital outlay in the outside wire plant would be exhorbitant if some such reduction were not possible for not only would all loops have to be run with four conducting wires, but the switching problem in the terminals would be quite complicated. In the 2-wire circuit, the system is still operated in full duplex, but the problems of trunking, switching and multiple connections are greatly simplified at a great saving in equipment and money.

In this circuit, (Figure 1(c)) the anti-sidetone coils act as directional couplers at each station. The degree of R-W channel crosstalk is a function of the balance and return loss of the impedance net Z. This net, for zero cross channel coupling, must exactly match the line impedance both as to magnitude and phase at all transmission frequencies. It is not too difficult to obtain an impedance network of this kind which will perform satisfactorily at voice frequencies on wire lines, but as the frequency goes up, it is

increasingly difficult to obtain the requisite degree of match, and is nearly impossible to perform at radio frequencies, although some progress is being made towards this end in the microwave region.

On wire lines, the differential in power levels on the send and receive channels at one station amounts to only a few db so that the return loss of the directional coupler need only be 20 or 30 db for satisfactory service. In radio, because of its low transmission efficiency as compared to a wire line, this power differential is of the order of 120-150 db and the return loss of the directional coupler for radio work would have to be 150 db or more to give adequate freedom from cross-channel modualtion. Such a loss is unobtainable at present though the dividends in research and development of such a de-coupler will be tremendous. It would then be possible to bring to radio all the flexibility of wire circuits, using the same frequency for both transmitting and receiving in full duplex on the same antenna. Until such a device is developed, it is necessary to develop the radio system design according to the principles of 4-wire circuitry.

A 4-wire mettalic circuit can be easily developed and built with full switching and multiple facilities.

Figure 1(d) illustrates the basic switch plan for just four 4-wire tandem connected circuits which are to be so arranged that any two may connect without hindering the operation of the other circuits, or three or more circuits may be connected in multiple with full duplex. All parties on such a circuit may freely converse exactly as though they were all gathered together in one place. Actually, full duplex is defined as a system which will allow transmission and reception of messages over a circuit simultaneously. When a 4-wire two station circuit is multiped with a third station, the circuit losses its full duplex characteristic, for the two directions lose identity at the third station and will mutually interfere. This represents no handicap for voice communications for it is entirely within the realm of ordinary human experience that a third person can understand nothing if two other people are shouting at one another and it is ordinarily expected that only one person shall talk at a time. This difficulty could be overcome by use of multiplex principles with frequency separation of the channel directions, or by direct trunking, but in either case the expense would be incommensurate with the returns.

On the switch frame of Figure 1(d), the number of switch operations required to complete a call is:

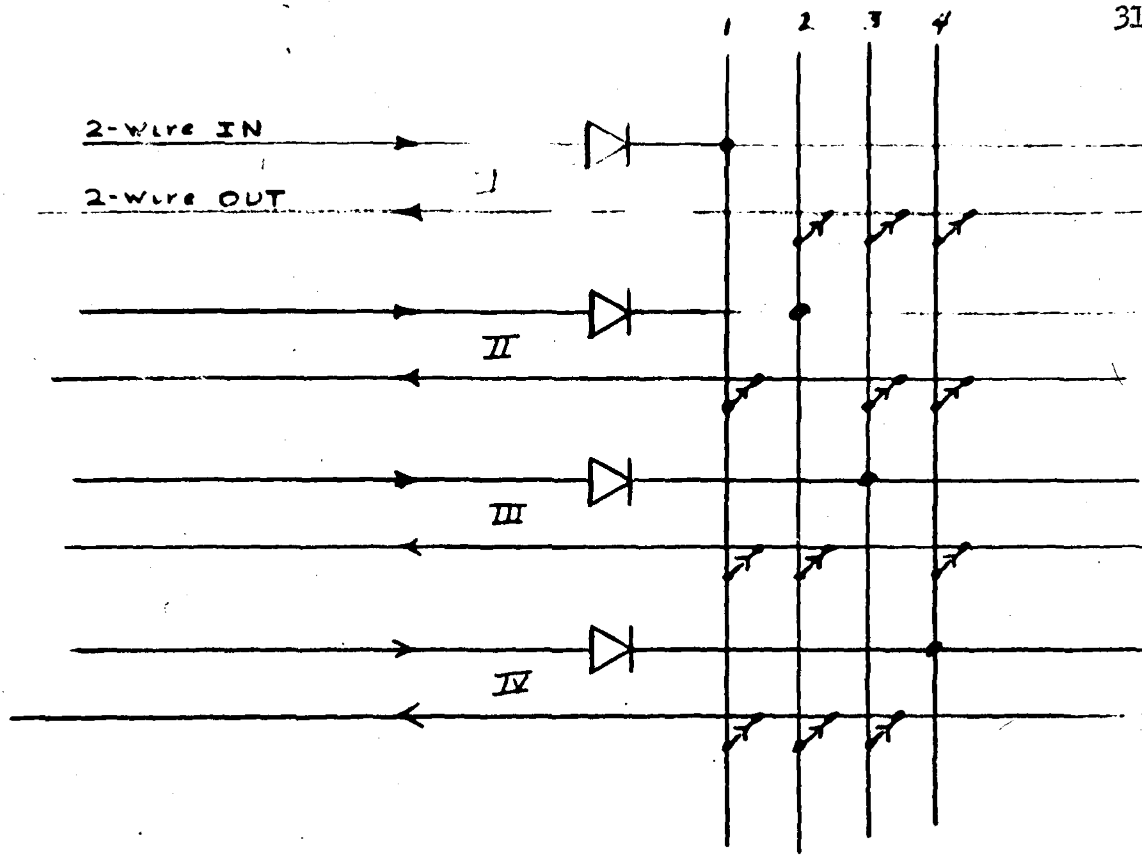


Fig.1 Four wire switching plan.

Send Channel No. (columns) / Receive Channel No. (rows)

	1	2	3	4
1		21	31	41
2	12		32	42
3	13	23		43
4	14	24	34	

Fig.1(e) Switch chart.

$$S = \frac{n!}{(n-2)!}$$

where n is number of stations required to be interconnected. It is readily evident that the number of operations mounts to astronomical proportions with even moderate multiple demands and the problem of actually building a switch board of this type would be most difficult.

For every switch that is closed, its conjugate on the switch chart (Figure 1(e)) must also be closed. When several circuits are to be interconnected, all switch points having the desired channel numbers for both digits must be closed. Thus, if channel I is to be connected to channel II, switch points 12 and 21 must be closed. If channels I, II, and III are to be interconnected, then switchpoints 12, 21, 13, 31, 23, and 32 must be closed. If one hundred stations are to be interconnected, 9900 switch operations are necessary.

To generalize the switch frame into a radio net, it is necessary merely to note that each tie point on the crossbars is equivalent to a radio transmitter, each switch point is equivalent to a radio receiver, and each vertical bus represents a separate operating frequency for the network. Thus, for a four station radio net operating in full duplex, there must be a

separate frequency for each station of the net, requiring four transmitters and twelve receivers. This is rather more equipment than is ordinarily justifiable for just four stations and, unless the requirements of the communication service between them justified this great outlay in equipment and monopoly of spectrum, some compromise mode of system operation can usually be found less demanding of equipment.

There is one interesting feature to be noted. The radio net is truly full duplex in operation and does not suffer the limitation of the equivalent metallic wire set. Traffic may be sent simultaneously between all stations without any limitations of interference. This is one of the advantages of radio nets; that the very nature of radio is a frequency discriminating principle which in itself constitutes a vast directly trunked system. Thus the equivalent to a new wire line can be established by a mere twist of the dial. Whereas in a wire plant, the cost of erecting and maintaining a wire line may be considerable, the radio line is "wire-less" and costs nothing. The discussion is now trespassing upon that region reserved for a later section and will be developed more fully in the consideration of trunking problems.

There are a number of ways in which the size and

expense of a 4-wire radio net may be avoided and yet retain most of the advantages.

One method is the familiar push-to-talk procedure of the police, airway, and military nets. This is a half duplex system; for messages can be transmitted in but one direction at a time. To reverse the direction of traffic it is necessary to alter the circuit configuration by a positive action of the operator. This system is very economical of equipment and frequencies but at a sacrifice to traffic handling capacity. In a true full duplex system operating on a 4-wire basis, the amount of traffic handled at any one station in the net (the total of incoming and outgoing messages) is equal to the number of stations in the net. In the push-to-talk system, the net can handle but one message at a time, for all stations share a common frequency.

The push-to-talk circuit is the nearest equivalent to 2-wire metallic net that exists in radio. The decoupling function of the hybrid coil is replaced by a transfer relay which alternately connects first the receiver and then the transmitter according to the will of the operator. It thus has most of the advantages of 2-wire systems with two very important drawbacks. First, when a station is transmitting, it cannot receive

too, and there is no way of breaking in on a circuit until the sending station releases it. Second, the operation of the transfer relay by a push-button is inconvenient and awkward. There are systems whereby the transfer is accomplished by voice operated devices which automatically transfer the send-receive function when a speaker starts to talk. These systems are so large and clumsy that they are generally not used if it can be avoided. But in all other respects, the push-to-talk technique offers all the advantages of connecting simplicity and economy inherent in the 2-wire system. The traffic handling characteristic could be improved by use of high speed telegraphy, or by providing multiple <u>independent</u> channels.

The TDZ-RDZ UHF equipment represents an attempt to improve the traffic capacity of the push-to-talk circuit by the provision of a number of separate channels which may be selected optionally by a dial selector device. While such a system will improve the overall network capacity, it is really little better than a single channel system as far as the individual stations are concerned; for they still have but one traffic carrying channel available at a time, (unless, of course, equipment is duplicated, in which case the system loses its economic advantage). If, within a

given net, all traffic is equally distributed amont the stations, both as to sending and receiving, this method of increasing traffic capacity will be satisfactory; but as soon as the circuit becomes unbalanced and all traffic tends to gravitate towards one particular station, all the advantage of multichannel operation are lost. Thus if within a ten station net, five of the stations originate traffic addressed, one each, to the other five stations, the traffic may be cleared simultaneously on five different channels. But if nine of the stations all originate traffic addressed to the one remaining station, the net might just as well have but one channel. The difficulty is, of course, that the TDZ-RDZ equipment has ten channels available which are mutually <u>exclusive</u>, while what is needed to improve the push-to-talk traffic capacity is to have <u>all channels</u> available <u>simulteneously</u> to <u>all stations</u>. This involves consideration of an adequate terminal system to control the net, for the problem of coordinating and controlling the communication activity of, say, thirty stations on ten different channels would be of superhuman proportions.

With but little design effort and slight expense, the control and circuit discipline features of communication system can be built directly into the system.

It takes experienced, well trained personnel to maintain circuit discipline on a crowded heavily loaded circuit. If instead of depending on human discipline and training to maintain order on the network, the equipment is so designed that a communication error cannot be made by the operating personnel, a large step will have been taken towards eliminating the need for trained personnel. It must constantly be borne in mind that one of the major aims of system design is to permit the operation of the system by inexperienced personnel with little communication background. The system must be so simple that any tyro can operate it, yet at the same time it must be foolproof so as not to upset the system in case of error.

It may be argued that manpower is cheap and there is no need to design expensive automatic equipment to do that which anybody can learn to do with time. We have paid the price for that attitude in the past with snarled communications, lost traffic, and ineffective operations. There are times when a message is of no use if it cannot be sent in seconds, and there is no time then to hunt for channels or beg for priority. The equipment must be inherently able to find or create a clear channel whenever needed, and only a machine can do it fast enough.

The TBS was the workhorse equipment of the past war and did yeoman duty as a fleet tactical circuit. It had, however, two glaring faults, not from the equipment design viewpoint, but from the system design aspect. The transmitter was, in the normal idle condition, completely deenergized and required about thirty seconds warm-up before it could be used. This delay proved unacceptible under operating conditions and the transmitter was often kept in continuous stand-by, a condition for which the equipment was not designed, with subsequent maintenance troubles in the power units. A design alteration was finally made which allowed instant operation without warm-up. A more serious defect was the absence of lock-out to prevent interference by undisciplined transmissions. When two stations are transmitting on a push-to-talk net, neither station is moniterins the transmission and is thus not aware of the interference. The result is that both transmissions are mutually garbled. The answer is lockout device which will not allow more than one station on the air at a time. Even in very urgent cases, it is usually less confusing to allow current traffic to be completed rather than trying to interrupt the traffic. In a push-to-talk circuit, there is no hope of interrupting existing traffic anyway so it would be

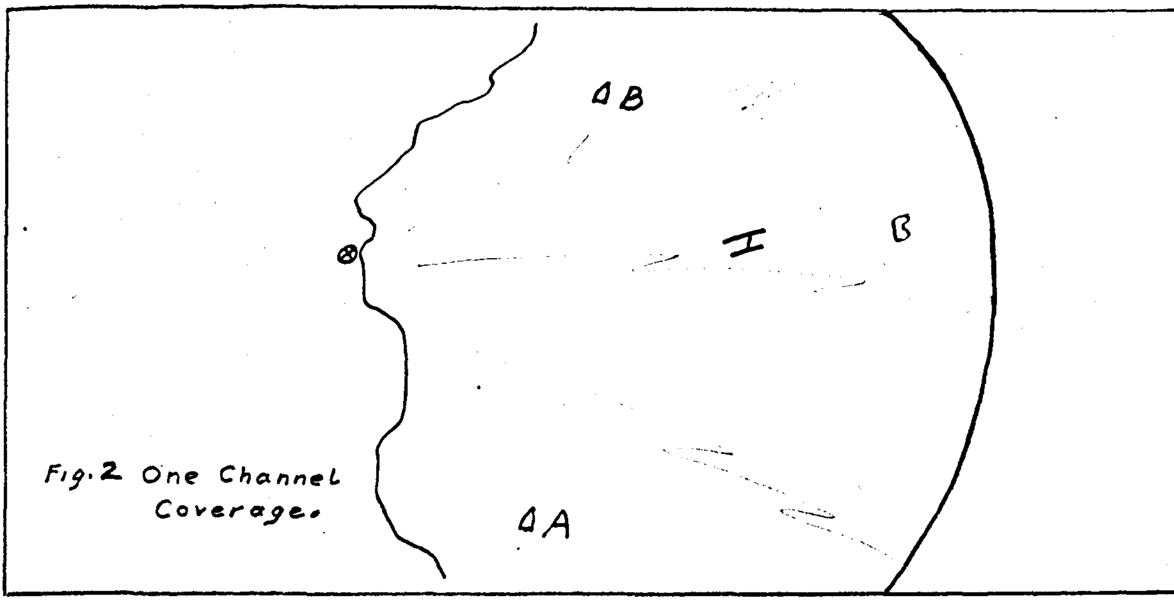


Fig. 2 One Channel Coverage.

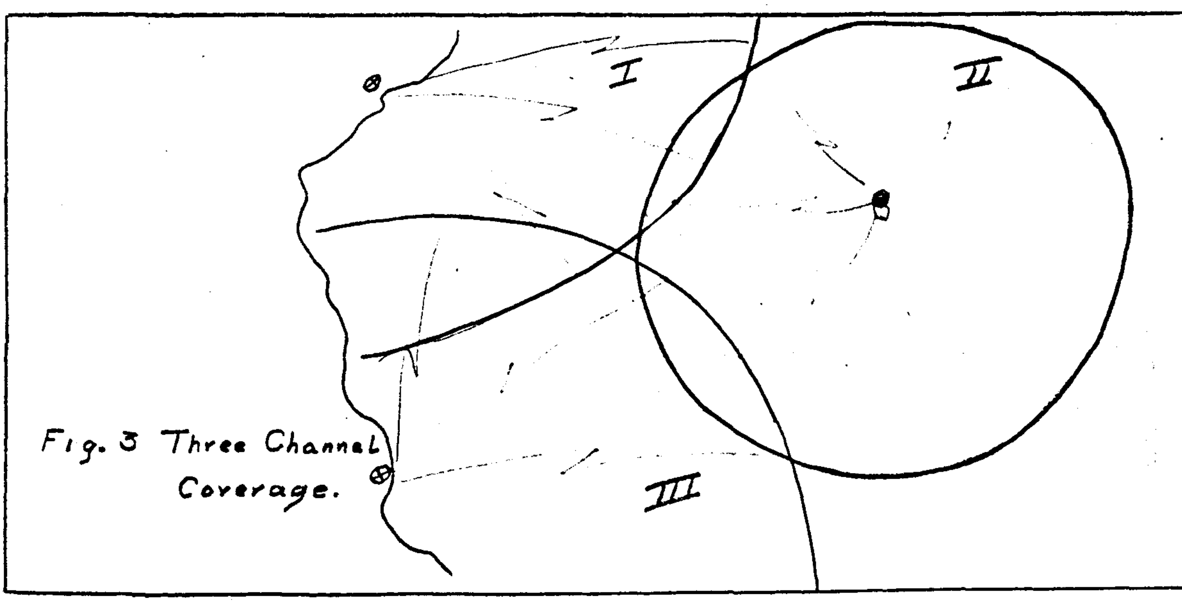


Fig. 3 Three Channel Coverage.

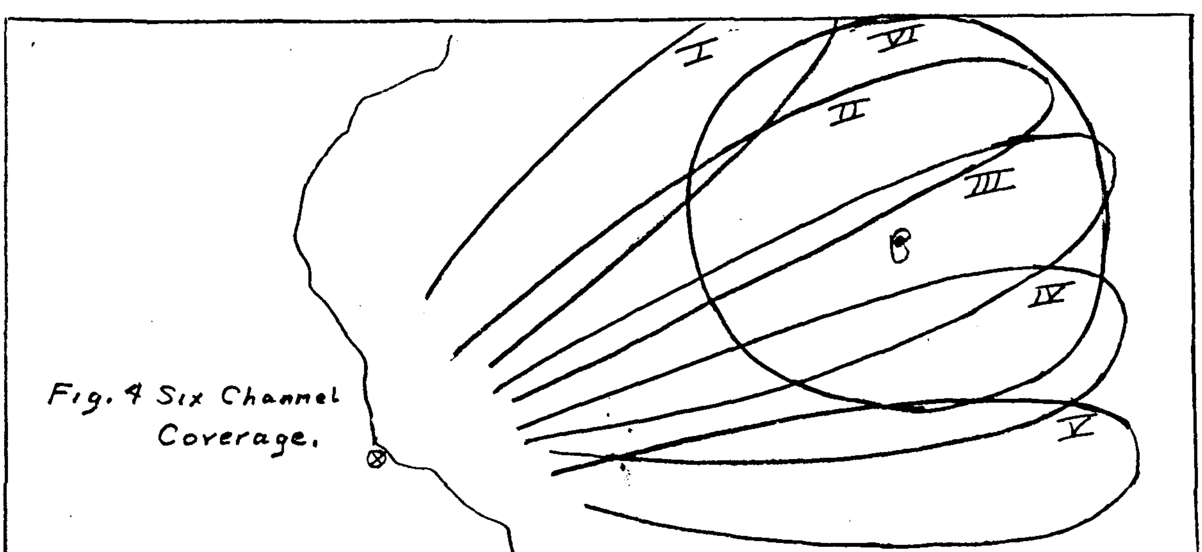


Fig. 4 Six Channel Coverage.

far better to prevent destruction of that traffic by attempts to break-in. Such a device was never built into the TBS system although its inclusion would have been a very simple matter.

The simplest type of communication net is the broadcast network. The transmitting station sends "one-way" without requiring or waiting for answer or acknowledgement. Figure 2 illustrates the simplest feature of a broadcast system. Since only one transmitter is used, the entire area is covered by but one channel, and station A must share the same incoming channel with stations B and C. This means that station A must guard and copy all traffic, even that addressed to B or C, in order not to miss any traffic addressed to A. This represents waste time as far as A is concerned, both in man power and equipment, and should be eliminated. Figure 3 illustrates three channel coverage of the same area wherein three low power stations handle the traffic on a basis of geographic distribution of addressees. This method may be termed as space channeling, for the stations are widely separated and may (or may not) operate on the same common frequency. With this coverage the three receiving stations will receive only traffic addressed to them and the system capacity is tripled.

If the transmitting stations are geographically separated and operate on separate frequency channels as well, generous overlap may be established giving complete coverage to a large area of mobile operations. The mobile stations now need to change frequency as they pass from one area to another, but this is no great handicap. The principles of space channeling and frequency channeling could be carried out <u>reductio ad absurdum</u> to the extent that each little area will have a separate channel for traffic delivery and no station will ever receive traffic not addressed to it. Figure 4 represents six channels covering the same are of Figure 2 giving a sixfold traffic capacity to the system.

There are definite tactical and strategic drawbacks to multichannel broadcast systems. First, space channeling will, by methods of traffic analysis, reveal the geographic distribution of the mobile units. Secondly, frequency channeling, will reveal the operational organization of the mobile units. (Assuming that the frequency channels are assigned on an organizational basis.) It could equally be argued that, with modern methods of reconnaisance and intelligence, these matters are not secure from enemy detection anyway. Nevertheless, there is no need to make it easier for the enemy to determine these matters and some basis for channeling

which would conceal these facts should be devised. The possibilities of greater traffic handling as against the possible disadvantages of decreased security must be balanced. With judicial design and operation there should be no loss of security involved and the advantages will far outweigh the disadvantages.

One basic principle of systems design is here illustrated. From the economy and security viewpoint, one centrally located powerful station is the best for broadcast service. From the aspect of traffic capacity and speed, numerous small low powered stations are required. The two are not reconcilable except on a compromise basis. This basic principle is equally applicable in other services but not so readily evident.

The greatest volume of traffic, both commercially and militarily, is carried in point-to-point networks. Such circuits are established under very stable operating conditions and are ideally suited to the employment of all the technical tools available to the communications engineer.

With the outbreak of war, the point-to-point naval communication net was the first to feel the weight of the growing traffic, for all fleet and shore establishment traffic eventually passes through some point-to-

point trunk for ultimate delivery. Consequently, the point-to-point nets received the full attention of the communications experts while the fleet communication problem went begging. There are no particularly difficult system problems in point-to-point communications and it offers the greatest scope to the engineer in multiplex and high speed techniques. The greatest problems involve trunking patterns and channel efficiency.

When it becomes necessary to provide connections between many stations, there are but two ways these connections can be made; either direct or in tandem. Figure 5 demonstrates the large number of trunk connections needed for direct trunking. Figure 6 illustrates the alternative form of trunking wherein all stations are switched through a central control station C. In practice, a combination of direct and tandem trunking is employed in conformity with a General Switch Plan based on study of traffic experience. In general, large centrals having large volumes of traffic are directly trunked and the smaller centrals required to tandem connect through the larger ones.

The tandem net has the advantage of employing a fewer number of more efficient trunks, but suffers in that traffic at the central station is in competition

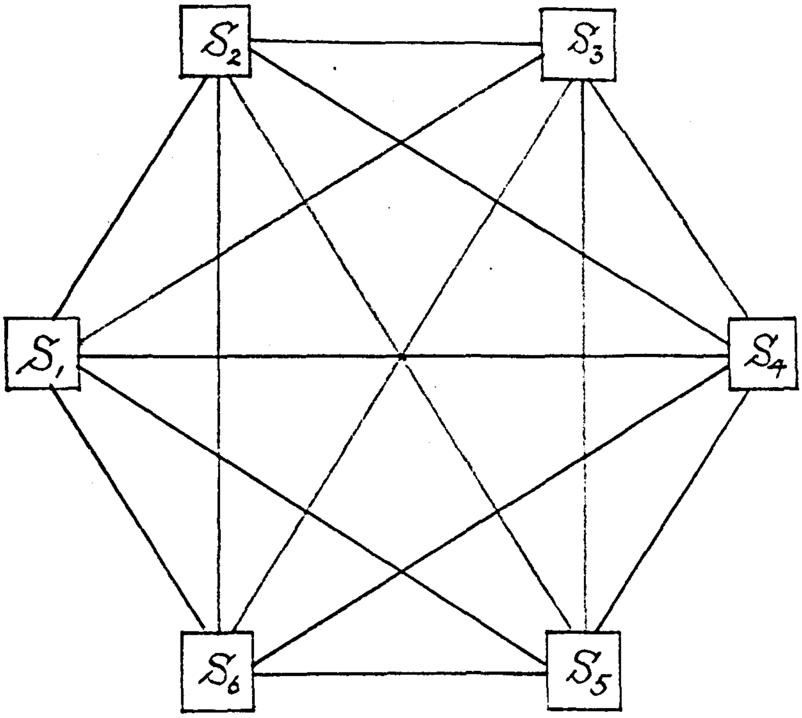


FIG. 5 Direct Net

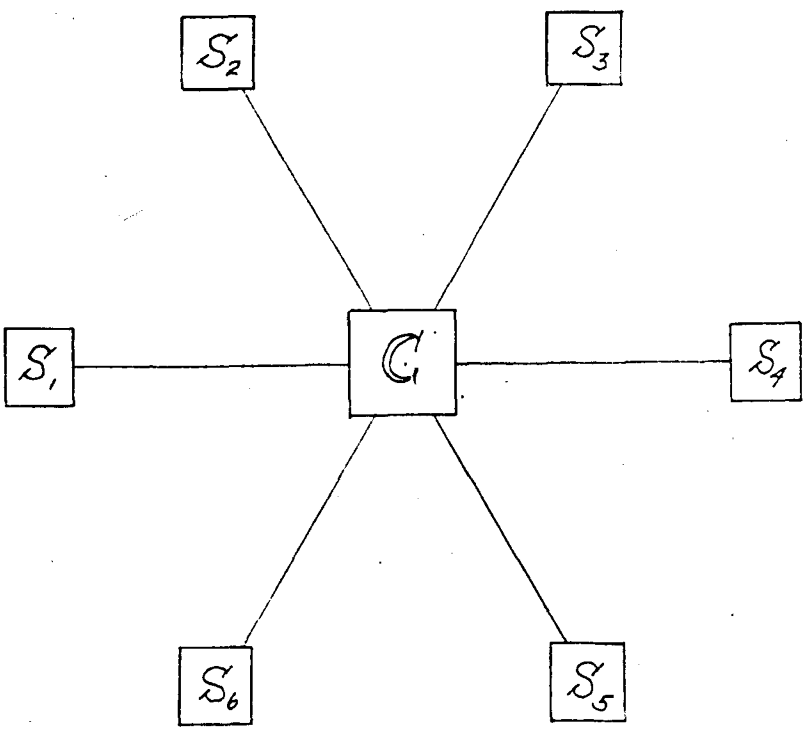


FIG. 6 Tandem Net

for any particular trunk which reduces the traffic handling ability of the system. Also each station is entirely dependent upon one trunk line, which, if destroyed, will isolate that station from the net. A direct net is more expensive but has the advantage of greater traffic capacity than a tandem net. It has been pointed out that a radio net is inherently a directly connected system for it costs nothing to broadcast to several stations at once, whereas in the equivalent wire net, each station must be connected with a separate pair of metallic conductors. Thus a radio net can enjoy all the advantages of direct trunking without the added cost to the outside plant, and the tandem trunk possibilities can be reserved for relay communications.

There is a definite limit to the number of times a circuit may be tandem trunked without excessive degradation, unless the intelligence can be regenerated in the tandem central. Each connection of the circuit will add a certain amount of noise to the circuit until finally the signal-to-noise ratio will be unacceptable. Generally, if the overall circuit loss exceeds 30 db, the circuit merit will become marginal, and this determines, in conjunction with the loss per connection, the number of connections that may be made.

Provisions for relay connection require the most

rigid overall engineering standards, for all circuits must be able to interconnect without reacting adversely on the other connections in the circuit. A circuit from A to B may be entirely satisfactory, and likewise for a loop from B to C, but, unless overall engineering standards of a high quality are maintained over the entire system, a tandem connection of A to C through B may be unacceptable.

If noise considerations determine that the maximum tandem loss cannot exceed 30 db, and it is desired that it should be possible to make four tandem connections, the loss of each trunk cannot exceed 6 db. Thus in any relay net, the quality of each trunk must far exceed the permissable standard of the overall relay, both as to bandwidth and loss. And further, these standards will have to be maintained with unrelenting attention throughout the network, for if even one part of the circuit is substandard, the entire connection will be rendered unacceptable.

Figures 7, 8, 9, 10, and 11 are self evident illustrations of radio nets employing various trunk plans. Figure 7 represents the plan of the common push-to-talk net with several channels available common to all the stations. Figure 8 is a full duplex circuit. Note that

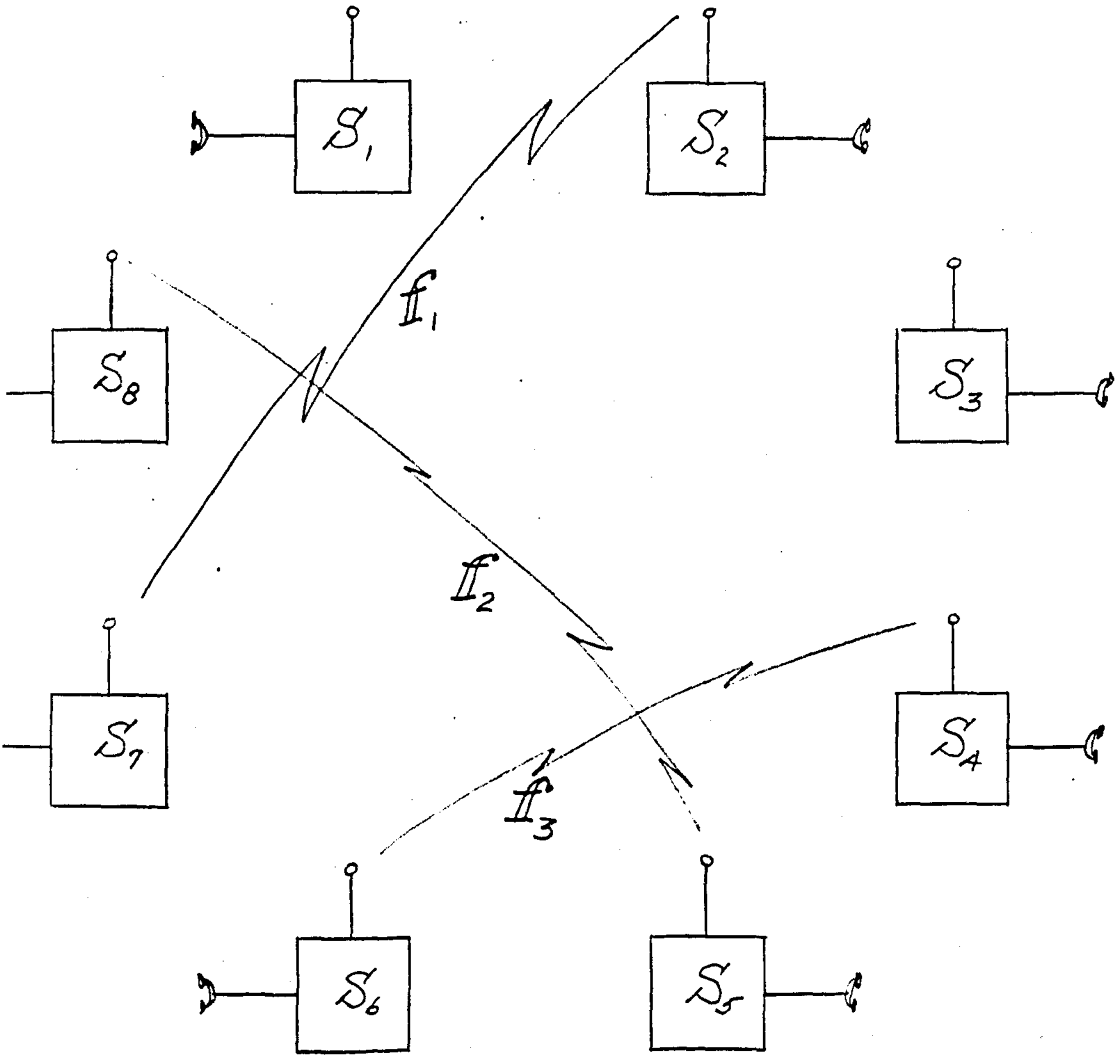


FIG. 7 Direct Radio Net.
HALF DUPLEX

Trim 8x12½

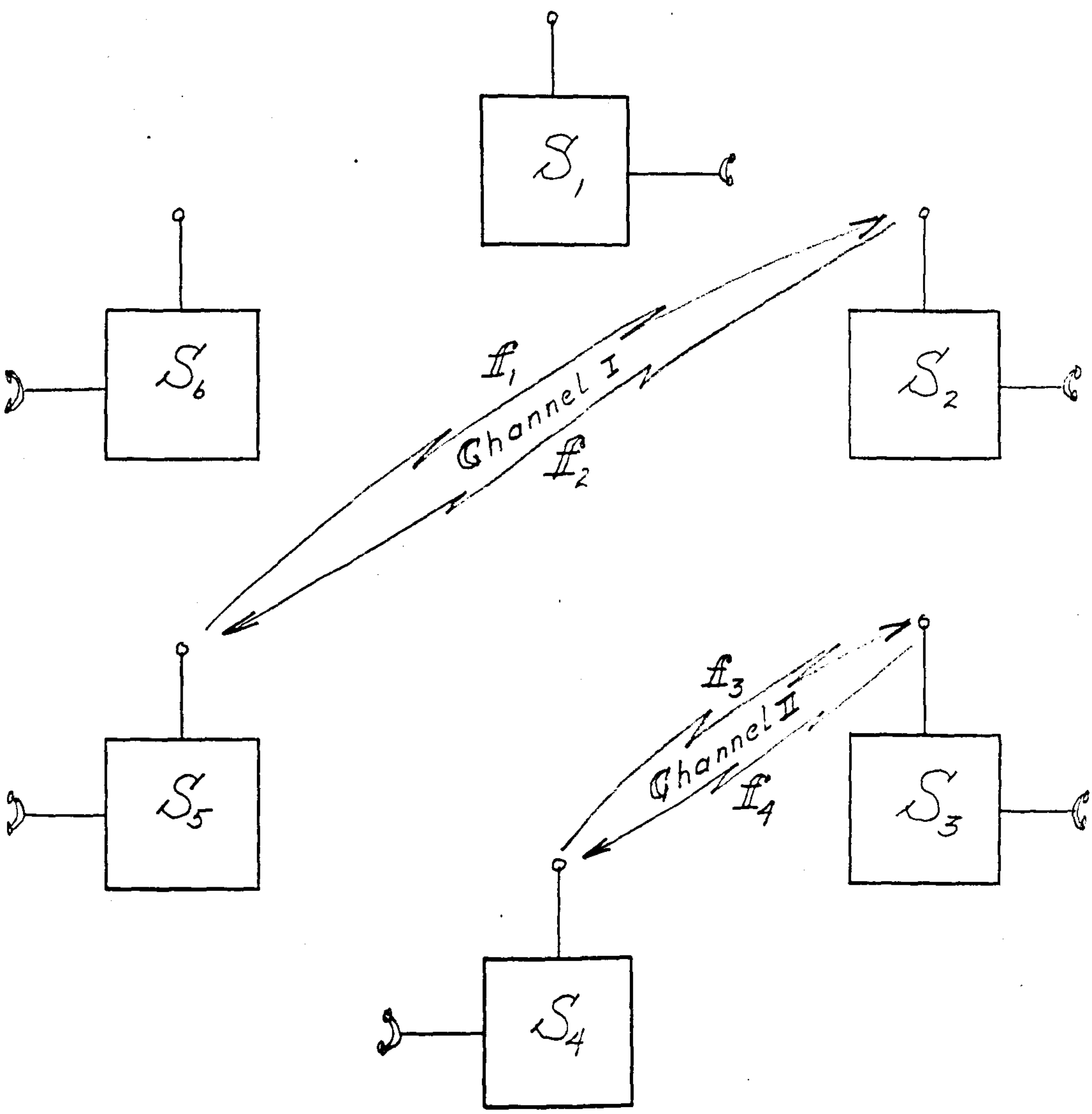


FIG. 8 Direct Radio Net.
FULL DUPLEX

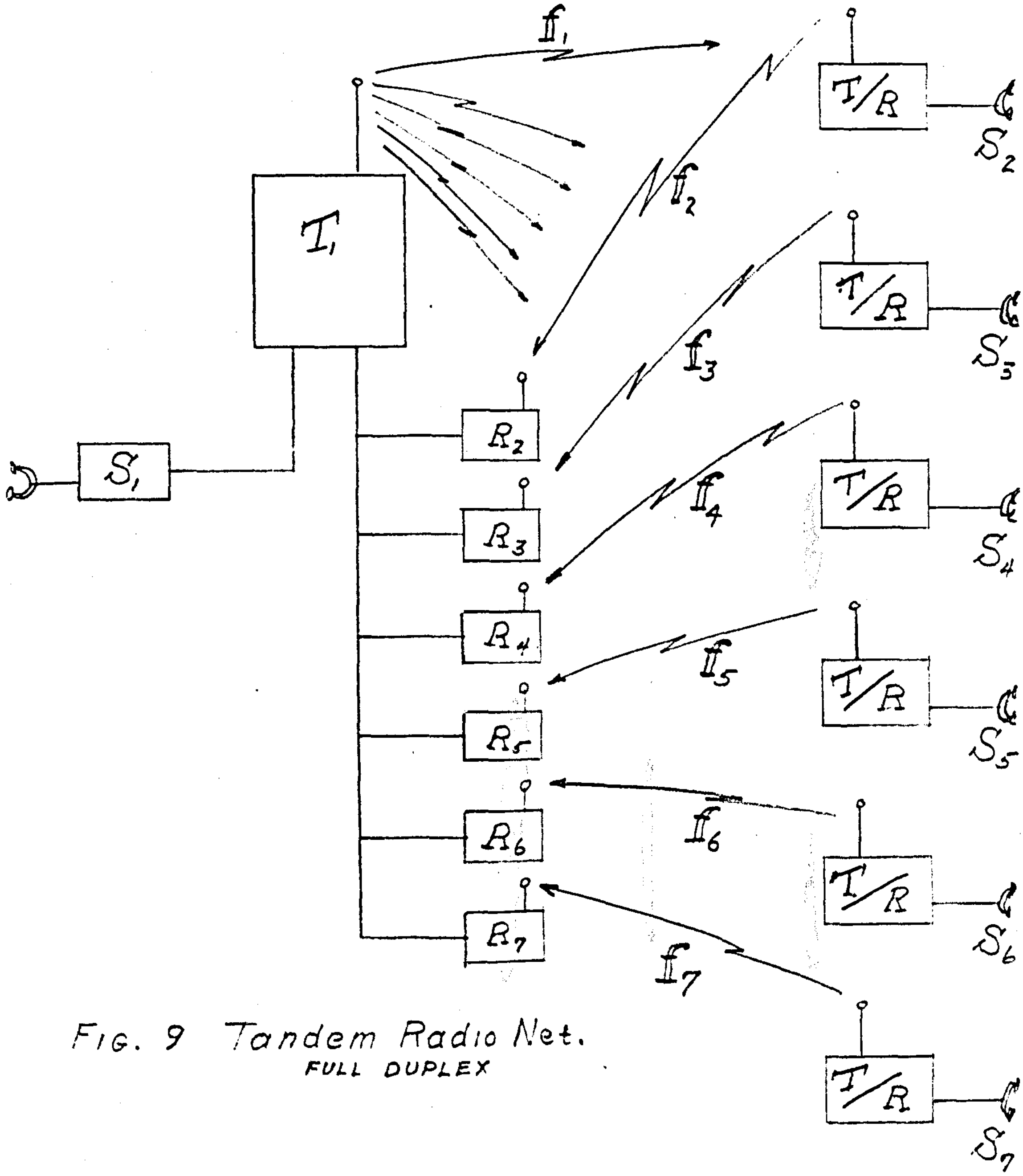


FIG. 9 Tandem Radio Net.
FULL DUPLEX

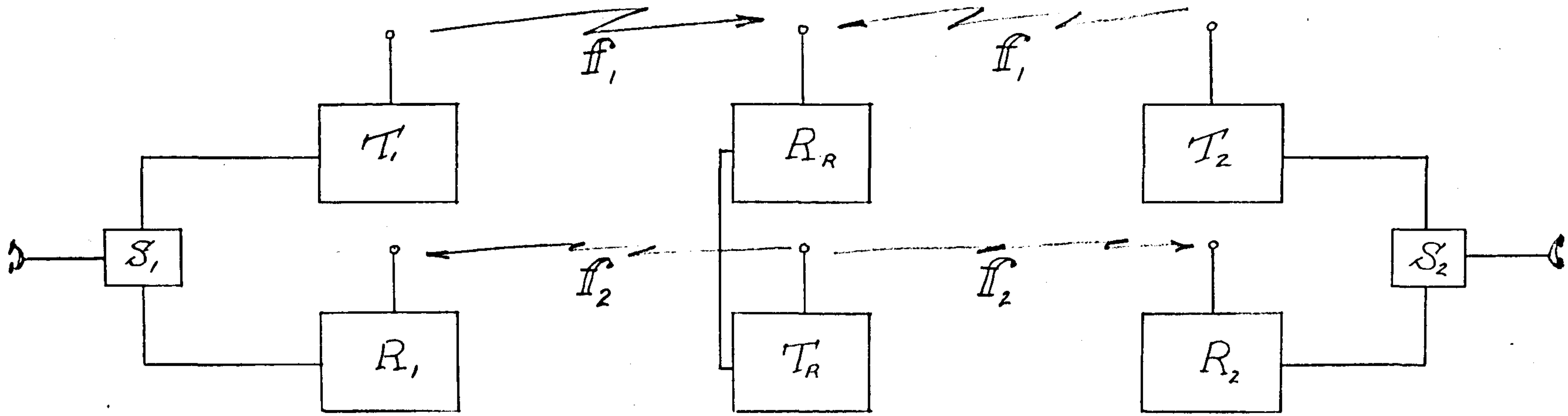


Fig. 10 Single Station Relay.

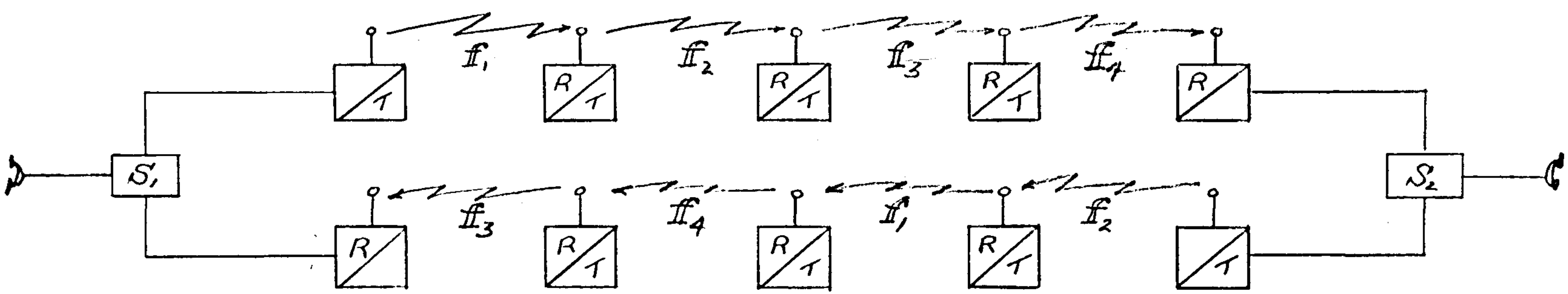


Fig. 11 Multiple Station Relay.

there must be as many frequencies employed as there are stations in operation, if there is to be no mutual interference. Figure 9 shows a tandem radio net in full duplex. Again note that there are as many frequencies employed as there are stations in the net, although here there is but one channel. It is inherent and axiomatic that there must be as many frequencies employed in full duplex operation as there are stations to be served.

Figure 10 is a single station relay net. It cannot be extended any further than as shown, and if a further system extension is required, it must be obtained by some such relay system as Figure 11, (although it may be extended by connecting S_2 to another link employing two other frequencies.)

After this elementary consideration of communication circuits, it is time to consider some of the more detailed technical aspects of Systems Engineering.

IV SYSTEMS ENGINEERING

Systems engineering divides naturally into two major provinces; those of transmission engineering and of switch engineering. The former has as its field all the considerations of traffic, trunking, line levels, amplifier gains and circuit losses, crosstalk, multiplex

operations, etc. or in short, all the forces that move traffic in the communication network. Switching must arrange for signalling, selection, controlling, supervising, guarding, and all the functions which guide traffic in the system. The concept of transmission is familiar to anyone connected with radio communications, but the concept of switching is one that has grown almost entirely from the art of telephony. The telephone companies early realized that to make the telephone economically feasible it must be so simple as to require no experience or technical training to operate it, and it must be so inexpensive that everyone could afford to use it. The problem of switching is inherent in the telephone system, and if it were to be done on an entirely manual basis, the operating staff would be so large as to make the cost incommensurate to the quality of service that could be rendered. The cost aspect was early understood and the invention of the automatic telephone switch system followed that of the telephone itself by only three years.

This paper is basically concerned with the idea that systems engineering has not been fully exploited and applied to naval communications, particularly the aspects of controlled selection and switching, and automatic traffic handling in fleet circuits.

1. Transmission

The most fundamental problem of radio communications is that of propogation and reliable range. The definition of reliable range is necessarily an arbitrary one for it is dependent upon what is considered a satisfactory signal level. At a given range, an adequate signal level for one type of service or equipment may be entirely inadequate for another.

The characteristics of radio propogation are well known and voluminous data have been obtained on propogation at nearly all frequencies. For purposes of system design, the spectrum may be divided into three essential bands. 2

1. Low Frequencies. (1.5 mcs. and below) Basic propogation is of the ground wave which suffers but low attenuation. Range (for a given field strength) varies directly as the square root of the power and inversely to the frequency. Propogation is but little affected by ionosphere condition or solar activity. Field is remarkably steady and free from fade particularly at the very low frequencies. Noise level is highest in this band with a diurnal and seasonal variation in intensity.
2. Medium and High Frequencies. (1.5 - 30 mcs.)

Ground wave highly attenuated and little used except for short range low power systems. Sky-wave propogation is a complex function of frequency, inospheric condition, solar activity, relative geographical positions, etc. and relatively independent of transmittor power. The field intensity is variable with distance and subject to fade with time due to variable multipath reflections from the ionosphere.

3. VHF and UHF (30 mcs. and above) The propogation characteristics of the radio wave are quasi-optical and partially predictable by optical theory. The circuit coefficient is relatively independent of all variables and remains constant within the service area which is determined as a proportionate function of the optical horizon. Field strength is independent of the ionospheric condition but fade effects are sometimes experienced because of multipath reflections from the surface of the earth.

Each band is inherently better able to provide some types of service better than the other bands. The low frequencies are better able to provide long range circuits where reliability is paramount and cost considerations are secondary. The higher frequencies have

replaced the low frequencies for most of the long range point-to-point circuits because of the lower cost of the equipment and the fact that reliability can be made satisfactory by diversity reception of the skywave.

The UHF and VHF bands are in the process of exploration and exploitation and provide extremely reliable and stable service for short range systems such as police networks, mobile communication nets, and short distance substitutes for wire links. The chief advantages of this band are the high stability and large capacity of the circuits provided as against the low cost and compact size of the equipment.

The demands for radio service have so crowded the frequency spectrum that expansion has been required into the higher and higher ranges for more room. The frequency spectrum has a logarithmic structure which means that at the higher frequencies the available spectrum increases at an exponential rate. Since the spectrum demands of any particular service are independent of the operating frequency, more service channels can be provided in the same percentage band at the higher frequencies. A 1% band at 100 mcs. can carry 1000 times as much traffic as a 1% band at 100 kcs. More important, perhaps, the band width of tuned circuits is a fixed

percentage of the operating frequency. Thus the 6 mc. bandwidth required for television is as easily obtained at 60 mcs. as the 5kc. band required for voice at 60 kcs., and at 4000 mcs., we can easily put 480 voice channels in the same percentage band width. For these reasons the VHF - UHF bands are replacing the lower frequency channels wherever the limited range is not a limiting factor.

Since the range and usefullness of a circuit is determined by its signal to noise ration, the major problem of transmission engineering is to improve this factor.

Radio noise may be divided into four classifications, depending on origin.

1. Atmospheric noise.
2. Cosmic noise.
3. Man-made noise.
4. Receiver and antenna noise.

Atmospheric noise is dominant below 1 mc. as a function of time, frequency, geographic position, weather, and season of the year. Little has been done to reduce the effects of atmospheric noise although extensive studies are afoot to develop noise reducing circuits. The modulation systems which discriminate against atmospheric

and man-made noise are practically operable only in the regions above 10 mc. and in that region atmospheric noise is of negligible importance.

Cosmic noise originates in outer space and represents a universal noise level at about -10 db (referred to 1 uv/m). In the absence of man-made and atmospheric noise, cosmic noise represents an ultimate limit to system sensitivity.

Man-made noise is the noise of civilization generated by electrical equipment and machinery which produce noise radiation. Like industrial audio noise levels it can be reduced only by a concerted effort on the part of the designers of the offending equipment. For isolated stations, such as ships at sea, a real effort to reduce the electric noise level could pay real dividens in increased circuit merit of the communications circuits. Man-made noise is dominant in the range from 1 mc. to about 500 mc.

Receiver noise represents the internal random noise of resistors and vacuum tubes of the transmitting and receiving equipment. This represents the most fertile field for scientific design reduction of noise in communication circuits but there are theoretical limits to the amount of reduction that can be accomplished. Comparisons of actual receivers are made to an ideal receiver having noise derived only from the antenna

radiation resistance, the irreducible minimum. Noise figures for ordinarily good receivers run from 10 db. (above ideal receiver noise) in the frequency range up to 500 mcs., to 15 or 20 db. for receivers operating in the range of 1000 mcs. and above.

Noise reduction is an important aspect of systems engineering, for the one aim of system design is to obtain the best communications with the least amount of equipment. A 10 db. improvement in circuit noise figure is equivalent to increasing transmitter power by a factor of 10, a saving not to be lightly ignored. The minimum C/N ratio which produces a satisfactory communication circuit is 10 db. with a 20 or 25 db. ratio being required for good quality circuits to carry voice, facsimile, etc.

Since noise is proportional to the square root of the band width, the best circuit noise figure can be obtained with the narrow band services such as Morse telegraphy and teleprinters. For modulators requiring a greater band width, such as voice, facsimile, etc., such special systems as single or assymetric side band modulation improve the C/N ratios over double side band modulation by decreasing the band width spectrum. Since noise is generally distributed uniformally with frequency

(within any small band) and has an amplitude modulation characteristic, narrow band FM systems naturally discriminate against noise to a certain extent. The pulse modulation systems, because of the high pulse peak powers employed and the techniques of limiting and clipping offer systems which inherently give very high S/N ratios. The alternative to reducing noise is to increase the carrier (i.e. transmitter) power. It is generally less costly to reduce noise than to build and operate larger transmitters.

The next most important aspect of transmission engineering is circuit stability. As opposed to noise, which is the problem of adequate circuit quality, stability is the problem of maintaining the circuit connection and guarding against interference with or by other circuits. This is for the most part a problem of technical equipment design. Radio transmission involves the generation and radiation of electrical energy of a particualr frequency and receiving that particular frequency by a selective receiver. The stability of the circuit will be a function of the stability of the transmitting device as to frequency and power level, the efficiency of the transmitting medium, and the selectivity and frequency stability of the receiving device.

Frequency stability of both the transmitters and

receivers is determined by the technical aspects of circuit design subject to the restrictions of law and international agreement. For the purposes of establishing order in the radio spectrum, the laws define the maximum instability to be allowed in the various frequency bands but for many services greater than legal stability is required. Services that require great selectivity also require great stability for excessive frequency drift will destroy the circuit connection. The exact amount of drift to be allowed is determined by a complex consideration of side band spectrum of the transmitted signal, the selectivity characteristic of the radio receiver, and the amount of side band energy that can be lost before the intelligence contained in the side band is seriously affected. In general, the amount of drift of either the transmitter or receiver cannot exceed one quarter of the receiver selective band before the intelligence is seriously impaired and it is usually necessary to maintain stability well below this limit. Thus if the transmitted spectrum is 10 kc. wide, and the receiver has a 10 kc. band width, the transmitter and receiver would have to be maintained on frequency within about 1 kc. to maintain an adequate circuit merit. This degree of stability is more difficult to maintain the higher the operating frequency and will require a relax-

ation in the receiver selectivity in order to maintain the connection. But to widen the receiver band width is to raise the noise level at the detector. An alternative method is to provide an automatic frequency control device on the receiver so that it will follow the transmitter in frequency drift. Either method is equally feasible and the choice must be made on the basis of the quality service desired, as against the considerations of cost and size of equipment.

Aside from the problem of merely maintaining the connection, there is the more exacting problem of preventing cross channel interference due to the instability and inadequate selectivity. The problem here is self explanatory. With frequency spectrum at a premium, it is becoming increasingly important not to lose any of the spectrum to excessive guard margins on the channels. It is desirable to space the channels as closely together as is consistent with channel stability and selectivity. The consequence of instability are here more serious than in the previously considered circumstance, for it involves interference with other channels as well as the loss of own channel. Once a channel allotment has been determined, it is imperative that the operating channels remain within their assigned frequency band.

When operating a multipoint net, stability is a very serious consideration. If one transmitter is sending to several receivers, all receivers must be kept on frequency with the transmitter, a more difficult problem than in direct point-to-point nets. In fact, stability has a very great bearing on the reliability of the circuit for naval communications. If there is any question that even one station will fail to receive a message, the circuit is unreliable, so if one of the many stations fails to maintain frequency, the entire system is discredited.

There is another source of cross channel modulation which is very difficult to eliminate; that due to spurious radiations and responses. These are most seriously present in nets consisting of many stations in close proximity, for otherwise the effects are usually down 30 to 80 db. below the main carrier, depending upon the particular equipment. Well designed transmitters will have spurious radiations down at least 60 db. below the carrier, although more would be desirable.

Receiver responses are a bit more complicated. Spurious responses are due to (1) image-frequency signals; (2) signals of intermediate frequency; (3) harmonics of the intermediate frequency generated by

the second detector; and (4) harmonics of the incoming signal generated in the converter tube. A receiver may have very good discrimination against adjacent channel cross talk but may have spurious response due to one of the above. A good receiver will not respond to spurious signals giving input voltages of 5-15 micro volts, depending upon the frequency.

The entire problem of spurious responses and radiations requires close attention by the systems engineer no less than by the equipment engineer. And there are not only the spurious responses inherent in the equipment itself, but there are also external spurious signals, or "stay" noise, developed by nonlinear or rectifying connections in the vicinity of the receiving equipment, such as in conduit joints, cables, light wires, etc. which develop all manners of harmonic and beat frequencies. This is particularly evident in shipboard installations where so much communications equipment is concentrated into such a small space. The communications systems designer cannot blithely select the few frequencies he will need and then ignore the multitude of parasitic radiations which he has conjured up.

Once the engineer has selected the operating band for the particular communication system he is to build,

it is necessary that he decide upon the method of modulation he is to employ. From the systems viewpoint, the exact method of performing the modulation is not as important as determining the advantages and disadvantages, transmission-wise, of each of the modulation processes in terms of transmission circuit constants. In Table I are appended some of the salient data on the transmission characteristics of each of the modulator and modulation systems listed below. The basic building blocks of radio transmission engineering may be set forth to show their relation, the one to the other.

Sense	Carrier	Modulators	Modulation
Sound	Radio	Hand key	Amplitude
Sight	Wire	Automatic Morse	Frequency
	(Light)	Facsimile	Phase
	(Infra-red)	Telephone	Pulse
	(Supersonics)	Television	a.position
		Teleprinter	b.width
			c.amplitude
			d.numbers

The criteria of excellence should be how faithfully does each system transmit information? how fast? how reliably? how much training is required?, and how much will the equipment cost, in size and weight, as well as money? The ideal communication system should approach mental telepathy for economy of equipment, speed, and independence of physical barriers, though mental telepathy leaves much to be desired as to reliability.

2. Switch Engineering

Switch engineering is the second major province of systems engineering. As a branch of the electrical or electronic sciences, it has had little wide spread attention and has remained an esoteric art, rather than an exact science, until very recently.

Switching involves an almost infinite number of permutations and combinations of the simple operation of opening or closing a circuit by means of a switch. It is the boast of the switch engineer that any complex series of operations can be performed automatically by electric relay circuits faster and more accurately than by humans. And the operations need not be confined to the mere opening and closing of switches, but the processes of hunting for and selecting the correct switch to be operated, ordinarily the domain of human operation, can be performed automatically with less fallibility than the human. In fact, given enough wire, relays, time, paper, and pencil, the switch engineer can design a circuit to perform any preset desired sequence of operations.

Therein lies the difficulty. The machine cannot think, and each operation it is to perform must be thought out by the human designer beforehand and built into the machine. Any operation not provided by the

designer cannot be performed by the machine, and the machine cannot react to unforeseen circumstances.

The first problem of the designer is to determine exactly what his machine is to do, not in general terms, but in precise step-by-step analysis of the operations to be performed and the contingencies to be met. Then, and not until then, the designer can sit down and calculate the relay circuits required to perform the steps.

The first part of such a problem is not too difficult for it involves functional considerations of operating factors familiar to every engineer. The difficult part of the task is the implementation of these considerations with actual equipment design. The switch engineer has, in the past, been a unique personage of great ingenuity and inventiveness, attaining his aims by exhaustive detailed examination of the problem and endless trial and error experimentation coupled with empiracal rules derived from past experiences or inherited from former masters of the art. Like an art, it has remained more a craft than a science, until recently, when a systematic analysis of the art of switching has produced, by the methods of statistical mathematics, a set of rules which clearly define the capabilities of any particular switch circuit. It is safe

to say that any desired sequence of operations can now be confidently provided by the switch engineer, which again throws the problem back to the systems engineer to decide what is wanted in the way of automatic switch facilities.

Since the machine cannot think, but can only provide a transfer of skill from the experienced designer to the inexperienced operator, it is manifestly impossible to require the machine to perform every possible operation required by unforseeable circumstances. The machine can only do that for which it was designed. This places a very strict limitation on the flexibility of a system that is built entirely dependent upon the limitations of the machine. But a naval communication system must be flexible above all. There must be provision for human direction and supervision. The human, it has been pointed out, has just about reached the full limits of his capability to provide direction to a complex com- comunications circuit. This is because he is required to perform many operations of discrimination and selection of a routine nature leaving little time for attention to the unique problems of communications. The machine can be a very valuable adjunct to the human in the realm of the iterative operations of everyday routine, leaving the human free to give his full attention to the pressing operational matters.

One of the major uses of switch circuits is that of selection; that is to pick out and connect one of a multiple of possible connections. This may be done in two ways: first, the selector may connect to a circuit on the basis of a set of determinate orders from a director mechanism, or secondly, it may connect in accordance with the requirement that the circuit to be connected must fulfill certain specific conditions. This second operation might be called hunting or searching, for it is forward looking, as opposed to selection, which is backward looking. The two ideas are similar but to different ends. Selection may be used to energize a particular circuit from a multiple, whereas search circuits will find the particular circuit of a multiple that is energized.

Switch circuits may perform a multitude of functions such as holding, locking, releasing, transferring, and interlocking which are useful in many ways. It is often desired that a certain circuit configuration be maintained indefinitely until a certain signal is received to break the connections. These are hold or lock circuits, depending upon how the operation is performed. The disconnecting signal then originates a release operation which breaks up the hold or lock circuit. The interlock circuits may determine the exact

sequence in which a complicated switch or transfer operation will be performed and will not allow false or unwanted signals to operate the sequence, nor allow essential steps to be omitted.

To proceed further is really fruitless for the number of possible functions which switch circuits may perform are infinite. It is not the intention of this paper to describe the art of switch engineering, but to mention the possibilities of the employment of switch engineering in naval communication circuits. The above mentioned operations are those of most interest in this discussion.

The most fundamental requirement before designing an integrated communication system, is the determination of an overall plan of connection and interconnection, that is, an overall trunking plan. This will determine which stations will be directly connected, and which will be tandem connected. Then it must be determined how these connections will be made, either automatically in response to calling signals, or manually. The combination of the trunking and switching plans form a General Switching Plan by which all design considerations are governed. The switching aspect is paramount in radio nets for nearly all nets are directly trunked

by the very nature of radio itself and the major question is then, how will the connections be made.

It has been mentioned that automatic terminal equipment lacks many of the advantages of the manual terminal in terms of flexibility and complexity of equipment. On the other hand, automatic equipment can perform its allotted duties faster and more accurately than the human can do them manually. It would seem, therefore, that a judicious combination of automatic and manual would have most of the advantages of both.

To illustrate this point, consider a system having ten separate communication channels all mutually available to all stations. It is desired that no circuit may be broken or preempted by other calls when a call is already in progress. A searching mechanism at the calling station is put into operation when the call is put up which tests all channels and connects to the first free channel it finds. The mechanism will refuse to connect into a circuit in which a call is already in progress. After selecting the channel, the sending operator may then send a series of calling signals which operate selection mechanisms in all the other stations. When the prescribed set of signals are received by the called station, its selection mechanism will operate to

complete the connection while all other selection mechanisms will refuse to connect. The incoming call would then be put up on a manual board in the called station only and the call handled from there to the particular internal substation desired. The automatic portion of the network has done the necessary job of selecting and guarding the communication channel yet the manual operation provides the necessary flexibility and human agency to handle the calls in an intelligent manner.

The requirements of a General Switching Plan are that all elements of the communication net be designed integrally to perform in a certain standard, predetermined manner. As long as each element of the net conforms to these standards, they may be connected in any manner prescribed by the General Switching Plan without fear of providing inferior circuits. The crudest illustration of this would be that it would not do for some stations to employ frequency modulation on their carriers while others employ amplitude modulation. This example is so blatant as to be ridiculous but there are other considerations more subtle that can cause as much trouble but are not so obvious. For instance, a General Switch Plan would have to specify the modulation levels of the transmitters and the conversion loss of the receivers, for all stations must, within certain limits,

provide the same signal level into the communication channel. To fail in this specification would mean that some stations would always be received better than others, or that some stations would receive all stations poorly, due to improper adjustment of the "line" levels. Such irregularities in the circuit coefficients would spell the difference between uniformly good communications and erratic, unreliable communications. This difference may hinge upon very small details. When a net is completely manual in operation, the human element may correct for many of the small errors that threaten to destroy communications, and each connection may be made on its individual circumstance. But when a terminal is operated automatically, or even partially so, the seemingly unimportant details of the circuit must be rigidly controlled if the system is to operate satisfactorily. To accomplish this aim, the General Switch Plan for the system must be very complete and detailed.

3. Component Design

This paper is not directly concerned with the aspects of component design except as it affects the operability and reliability of the system as a whole. Needless to say, inferior equipment will render inferior service. But in a large communication net consisting of many diverse but interrelated components, the

reliability of the system is not even as good as the worst component reliability. A good analogy may be made of the problem of equipment life as determined by vacuum tube life. If a piece of equipment has but one vacuum tube and it will last one thousand hours (assuming all other factors constant) the equipment will operate for one thousand hours without breakdown. But if the equipment has one thousand vacuum tubes, each good for one thousand hours, the equipment is due to break down once every hour. The analogy is apparent. As the size and complexity of an integrated system increases, the reliability of the component parts must be increased proportionately if the overall reliability is to be maintained.

Similar considerations are true for maintenance of system quality, as was discussed under the problem of tandem trunking. The capacity of each component link of the system must be greater in terms of band width, "line" loss, and distortion than that of the overall system.

4. Test and Maintenance

Maintenance plays a very large part in all phases of engineering, for machinery cannot repair itself. For complete reliability, trouble must be corrected, not

after it occurs, but before it occurs. Incipient troubles cannot normally be detected by ordinary operation of the system, but must be ferreted out by comprehensive detailed test of the system components, item by item.

Since the General Switch Plan determines the overall operation, it will also determine the operating condition of each of the components. With this as a starting point, it is then possible to develop test procedures to determine that each of the component elements is performing according to specifications. Further, if the system is thoroughly integrated, whole sections may be given routine periodic tests which will quickly determine satisfactory condition of the section. These tests could be given frequently and then, when trouble develops, the entire section can be tested unit by unit to isolate the trouble.

Human nature being what it is, there is no use having a test procedure that is awkward and inconvenient to employ, for then it will not be employed. The test equipment should be designed and built into the system as an integral part of the system and facilities provided to make test procedure as easy and convenient as possible. The test equipment should be installed at one

position convenient to the operating personnel and test outlets provided at that position to all the crucial test points in the system. Thus a brief routine operation at the test position will determine the operating condition of the system and adjustment can immediately be made to correct unsatisfactory conditions. Too, when trouble develops, it can be quickly determined and isolated by use of the test board.

V SYSTEM DESIGN

1. General Requirements

This section is intended to provide an example of the methods of system design as contrasted to the approach of technical design. It is the credo of the modern schools of architecture and allied branches of engineering, that form must follow function. In the past history of communication engineering this rule has been practiced in reverse, for the technical designers are little informed as to the particular requirements of naval communications and have provided equipment with excellent technical design but which lack the special features which make them especially adaptable to the naval organization.

The first step of system design is to state the use to which the communication system is to be put.

In intership communications, the problem of handling long administrative messages is a difficult one. They are usually too long to be sent via the tactical circuits and too complex to be intrusted to voice transmission. Visual means of communication are limited in range and in time. It is necessary that some new method of rapidly disseminating administrative information be devised that will not conflict with the existing tactical circuits, which will have a large traffic handling capacity, and will reproduce the messages at the receiving terminals in positive form.

In the absence of definite statistical information as to traffic experience, the following data will be assumed.

1. Types of service - - - - - - - - - - (In order of expected use)	Teletype Facsimile Voice
2. Average length of message - - - -	150 groups
3. Maximum number of messages per station served per hour - - - - -	3
4. Service area - - - - - - - - - - - -	25 mile diameter
5. Relay extensions - - - - - - - - -	75 miles (two tandem connections)
6. Circuit quality (Carrier/Noise) - -	20 db
7. Minimum line level - - - - - - - -	47 dbRN
8. Maximum number of stations - - - -	25

Specifications. Channels are to be provided in sufficient numbers so that, on the statistical average, there will always be a channel available for use. All channels will be available to all stations in the system but will be used on a mutually exclusive basis; that is, privacy is to be provided and the channels are to be invulnerable to inadvertent preemption by other stations when in use by one station. (Privacy requires a selective calling system and automatic lockout of unwanted stations.)

Teletype is to be the primary method of communication with alternative provisions for facsimile and voice. These facilities are to be provided at a number of substations within each station. The internal distribution system is to be kept separate from the main intership system through use of a manual board connecting from subsystem into the external system. The internal system will thus be available for intraship communications when not connected through the manual board.

2. System Design

The number of channels required for this system can be determined by the equation

$$N_c = \frac{(\text{No. of stations})(\text{Ave. length of message})(\text{Messages/station/hour})}{60}$$

$$N_c = \frac{(25)(3)(3)}{60} = 3 \text{ and } 3/4 \text{ (or 4)}$$

With four channels, the system will handle all the traffic among twenty-five stations with the probability that there will always be one channel free. This is based, of course, upon the predicated traffic experience outlined above, and if it develops that the average length of message is longer than three minutes, or that during the busiest hours there are more messages

originated than assumed above, the system will have to be expanded to provide additional channels.

For administrative traffic it is seldom necessary that the channels be full duplex, for administrative messages usually develop ideas or disseminate plans and information in considerable detail and do not involve the rapid interchange of thought and commands required in tactical circuits. The channels can thus be "one-way" or broadcast channels, with one station using the channel exclusively for transmitting, and all others remaining in a passive receiving condition on that channel. The system will then have four frequencies, one for each channel, and each station will have facilities for sending or receiving on all four channels simultaneously.

For several reasons, it may be desirable that no one station be allowed to transmit on two channels at once. One reason is technical in nature. With two transmitters operating in close proximity, the possibility of crosstalk and intermodulation is increased with interference developing on other channels. It is, from a systematic viewpoint, undesirable that one station should be able to "capture" more than one channel for this would decrease the number of channels theoretically

available to other stations. As a matter of good practice, each station should be limited to the employment of one channel at a time. This precludes the necessity of having four transmitters, and one transmitter per station will suffice, providing it is readily tunable to any of the four channel frequencies.

The system will take advantage of the direct trunking feature of radio to cover the service area, but beyond the service area, resort must be made to tandem trunking, or relay. This can be done in several ways, but only one will be described here as being the most satisfactory.

It is not desirable that any of the channel frequencies used in the service area be used for relay work, for this would reduce the number of available channels for general service. Relay traffic should be considered as separate from general traffic for it is not chargeable to the message count within the service area when taking data for traffic experience. Thus the figure of three messages per station per busiest hour is exclusive of relay traffic, for this traffic does not exist as part of the general area traffic, but is really switch-through traffic.

Referring back to Figure 11, it is seen that the

same two frequencies are used in alternate links of the relay. Starting at Station 1., frequency f_1 may be one of the general service frequencies and is picked up at the first relay station. The intelligence is extracted and used to modulate a special relay frequency f_2. This relay frequency does not then interfere with any of the other general area channels but occupies much the same position in the General Switch Plan as a toll circuit occupies in a telephone General Toll Plan. It is a special through circuit for the exclusive use of long distance traffic. This relay link is terminated at the second relay station which delivers the traffic on another one of the general service channels. By the use of one additional channel, the system has been extended through two relay points. With two relay channels, the system could be extended indefinitely (until limited by signal degeneration), with a reverse channel provided; or outgoing relay traffic can be sent on two channels from the same area, and relay circuits may pass through several general service areas without preempting channels reserved for local traffic.

3. Range of System

The service area has been defined as a circle of 25 miles diameter. This represents a constructive figure for the necessary area of communications for any in-

dependent command at sea. The actual service area is really not definable in geometric terms but is dependent upon the relative positions of the various stations to the center of gravity of the system. But if each station can provide coverage of 25 miles radius, the coverage area is then but 25 miles in diameter, for stations on the periphery of a 25 miles radius from the center of gravity will be then fifty miles apart and out of radio range. With use of VHF-UHF equipment, the radio path cannot be reliably extended much beyond 25 miles and thus represents the technical limitation to the range of the system.

The range of a radio link is dependent upon two factors; the amount of power in the transmitter, and the sensitivity of the receiver. But the sensitivity of receivers has reached the ultimate in that the random noise level sets the lower limit to the input sensitivity. In the VHF-UHF region, Figure 12 represents the threshold level of noise below which a receiver cannot go to detect weak signals. Below 300 mcs. the man-made noise predominates, but above 300 mcs. all external noise sources have disappeared below the internal noise sources of the receiver itself. At about 300 mcs. there is a minimum of noise in the radio spectrum.

Using the noise distribution Figure 12 and the well

Figure 12. Noise vs Frequency
(graph)

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established empirical formula

$$E = \frac{14\sqrt{W}}{d} \sin\left(\frac{2\pi h_t h_r}{l d}\right) \text{ volts/meter}$$

where E is the field strength at the receiving antenna,
W is radiated power in watts
h_t is the height of the transmitting antenna in meters
h_r is the height of the receiving antenna in meters
l is the wavelength in meters
and d is the distance between transmitter and receiver in meters.

(It is to be noted that this formula is valid only within the radio path horizon.) The carrier to noise ratio at the receiving station can be calculated. In Figure 13 this has been done for a radio path length of 25 statute miles (22.4 nautical miles) and antennae heights of 70 feet. For a given configuration such as this, the carrier to noise ratio rises at a rate of about 10 db. per octave. This is because of the decrease of effective antenna area as a noise receiving device (noise remaining substantially constant in field strength) whereas the carrier field strength increases with frequency to exactly counteract the decrease in effective antenna area. The curvature at the upper end is due to the sharp rise in noise level with frequency above 300 mcs. The dotted curve represents ratios more nearly obtainable with actual receivers for above 300 mcs. the receiver noise figure falls off at about the rate of 5

Figure 13. C/N Ratio vs Frequency
(graph)

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db. per octave or more. In plotting this curve the worst condition has been assumed as regards to noise level, receiver noise figure, receiver band width, etc. A receiver band width of 10 kc. has been here assumed though only 6 or 7 kc. will be required for the proposed types of service. Likewise the noise level assumed was that for urban districts which have above median noise levels. The result is that a system built on these conservative figures will operate better than required most of the time and will operate satisfactorily under even the most difficult conditions. This creates a reserve of "quality" against trouble from faulty equipment and provides a margin for relay operations.

The selection of as high a frequency as technical design is able to provide has several advantages.

(1) Reduced transmitter power requirements.
(2) Small physical antennae permitting use of arrays.
(3) Ample Band width available.
(4) Low noise.
(5) Fewer anomolous propogation effects.

From Figure 13 it can be seen that an optimum operating frequency would be at about 400-500 mcs., at which frequency a 35 watt transmitter would provide the specified 20 db. carrier to noise ratio. Because of the present frequency allocations of this band to aviation aids, radiosonde, and similar services as well as to military communications, it may be necessary to use a somewhat

lower frequency, say at 300 mcs. but only a slight difference in C/N ratio would result.

4. Modulation

Frequency modulation has one quality as a communication link not to be found in amplitude modulation. Much has been argued about the noise reducing capabilities of frequency modulation but the real core of the matter has been somewhat underemphasized.

The most difficult problem in radio communications is that of maintaining line levels constant regardless of weather, time, or varying geographical positions. With amplitude forms of modulation, the signal to noise ratio of the receiver output is variable with distance as the carrier amplitude decreases. Of the three attributes of a radio wave, amplitude is the most susceptible to distortion whereas frequency is the least susceptible to variation in the process of transmission. Since frequency, unlike amplitude, is invariant with distance, then the signal level in a frequency modulated carrier is independent of the radio path. This feature is very important in mobile communications where the radio path is continually changing. The fact that the signal level in a frequency modulated carrier channel will remain constant makes it possible to assign the circuit a

definite coefficient and to engineer the system exactly as though it were a wire line.

The chief disadvantage of frequency modulated systems is its susceptibility to interference, intentional or otherwise. The same capture effect, which makes frequency modulation so impervious to interference in fixed services such as broadcast, works to its disadvantage when used in movile services where it is apt to be in closer contact with unwanted carriers. If the wanted signal is as little as 6 db. stronger, the receiver will discriminate very heavily in favor of the wanted signal and the unwanted signal will not cause interference. But if the ratio is reversed, the unwanted signal will capture the receiver and block the circuit. This is serious in shipboard installations, for the spurious radiation of transmitters on other channels may easily be 6 db. stronger than the incoming signal and thereby block the circuit. With amplitude modulation, the interfering signal must literally "drown out" the wanted signal by sheer power and the amount of interference in the output is directly proportional to ratio of interference to carrier at the antenna. This is not so for frequency modulation, for there is an improvement factor operating in favor of the stronger signal. Unfortunately, the receiver is unable to distinguish which signal

is the wanted signal, but merely reacts in favor of the stronger.

The many factors concerned, when considered in their entirety, tend to favor frequency modulation. The fact that, within the service area, the circuit coefficient remains constant regardless of radio path promises more uniform and stable communications with frequency modulation. But also there are several other factors not to be ignored. With a given set of tubes, a frequency modulated transmitter may be operated to the full rating of the tube, an increase in power of about ten percent. The modulation equipment is negligible, for modulation may be performed at low levels and Class C amplifiers used thereafter.

There is no reason why the relay links cannot, on occasion, employ medium or high frequency amplitude modulated carriers for long distance links without in any way affecting the operation of the local service.

Having selected frequency modulation, it is time to consider the requirements of the types of modulators specified for service on this system.

The highest frequency required to be sent is 3000 cps. Both voice and facsimile require this band width

though the lower limit for voice is 250 cps. and that for facsimile is about 2100 cps. For teletype, it is possible to use frequency shift methods of modulation, for frequency shift keying is closely allied to frequency modulation. Without going into the technical details, it is possible to place any of the three types of modulators upon the carrier within the same band width and with the same frequency modulation deviation. Any of the three may be placed upon the circuit alternatively without any alteration of the equipment or the mode of operation of the circuit. Since this is a broadcast system, there must be a prearranged operating procedure, for there is no opportunity to talk back and forth on the circuit. It is expected that teletype will be the main service channel with facsimile and voice being used for special services. All stations will ordinarily receive with teletypes on the line and will shift to the other forms only when directed.

5. Switching

This entire system is dependent upon the successful design of the terminal selecting and switching equipment. Many of the functions required of the system can only be done by automatic switching and general employment of the traffic handling techniques developed in telephony systems. For flexibility and speed, it is necessary to

use both automatic and manual switching, with the automatic switching doing the vast majority of the work.

There are two requirements for this system; automatic lockout of unwanted stations, and privacy. The first can be provided by the use of automatic channel selection at the sending stations so that the equipment will never connect to a busy channel. The second requirement can be met by selective dialling connections at the receiving stations. Selective dialling can be made most flexible; and calls may be dialled to connect one station, particular groups, or the entire net may be dialled, calling in all stations for a general conference. Any dialling combination desired can be provided such that every ship, every command, and every command echelon could have separate call designations. In this way, the problem of channeling calls to the desired addressees is automatically solved. A destroyer squadron commander could connect separately to any one ship within his command, connect separately to any one of his division commanders, or connect to all of his division commanders collectively, or to any division as a whole, or to his entire squadron collectively, merely by dialling the correct combination.

Once a connection is made through the automatic terminal, it is put up on the manual board of the called

station. The four receiving channels are brought out at this board, along with the apperances for the relay link transmitters and receivers. Also appearing on this board are all the substations of the internal system. On incoming calls, the connection must be made through the switchboard (though it may be patch connected for any desired length of time) to the internal system which will have its own design pattern to fit the needs of the particular ship or station. The only requirements on the internal system of the station is that it meet the external system with a match in impedance, line level, and frequency response characteristic. Beyond that, the systems are independent. On outgoing calls, the order is given to the switchboard operator who then connects the internal system to the external system and dials. Upon release of the dialling key, his work is done.

The exact configuration or lay out of the switching terminal is not important in this discussion as long as the salient features of its operation are clear. The main points in its operation may be set forth in summary as follows =

1. <u>The Channel Selector</u> tests the output of each receiver (with CODAN) and will stop only on an idle channel. The stopping action of the selector also selects the proper channel for the transmitter, brings it to that channel, and puts it on the air. The lost time between channel selection and transmitter tune up must be small.

If the selector finds no idle channel, it will step along to a busy connection, and give a BUSY indication to the operator. The above sequence of operations is activated by the insertion of the input connection in the board.

2. The operator dials the desired station. The fact that there is now a carrier on the air prevents interference by any other station inadvertently attempting to use the channel. This provides lock out of other stations. An emergency provision could be made that the operator, by closing an emergency switch, could cause the channel selector to connect to the first channel in its course, and the transmitter then be energized. The operator could then break-in and direct the channels be cleared for emergency traffic. This detail would be quite difficult, and should be unnecessary.

3. The incoming signal operates the CODAN which connects to the selective ringer. The dial pulses operate the ringer and connect the receiver output through to the manual board. The operator answers the indicator light by connecting a teletype reperforator and awaits further connecting instructions. He may be instructed to connect through to some particular substation, or he may take the entire message on his reperforator and then retransmit on the internal system for delivery and routing.

4. The relay links are brought out entirely independent of the rest of the terminal and is handled on a full manual basis. Supervisory signals may be by voice, or by selective tones, from the sending operator.

6. Future Planning

This system has been built on the unit of four channels which is also the normal number of ships in a tactical division. On independent maneuvers, each ship in a division could thus preempt one channel and provide full duplex operation. There is no reason, however,

why switching provisions for, say, ten channels should not be built into the system so that it is merely necessary to add another transmitter and four receivers in order to double the system capacity. Large ships and commands might even have eight channels while the smaller units have but four. The channels would be split at the manual board so that the large units could use half the facilities for communications among themselves, reserving the other channels for the smaller units, which, though greater in number, do not originate so much traffic.

VI CONCLUSIONS

The successful systems designer must have three attributes.

1. Technical knowledge of the possibilities and limitations of electronics to perform required tasks in the projected systems plan.

2. Operational knowledge of the requirements of the particular service to be served coupled with a complete understanding of the philosophy and structure of communications.

3. Imagination.

The principles of systems design are very broad and defy strict classification. This is due in part to the many diverse purposes of communications systems and in part to the fact that any particular problem may be successfully solved in several different ways. It is

the attribute of imagination on the part of the engineer that enables him to devise and select the best solution for incorporation into the particular system under consideration. It might almost be said that the only really general principle of systems design is attention to minute details in synthesizing the solution, and strict adherence to the highest, most exacting standards of engineering design consistent with the economic considerations of the problem.

TABLE I

This table is not intended to be definitive in all the technical aspects of modulations and modulators, but is meant to provide salient information on the particular aspects affecting system design.

Voice telephony	Spectrum: 250-3000 cps. The human voice is a complex of the frequencies from 100 to 10,000 cps. but adequate quality is provided using only the band 250-3000 cps. The power of the voice resides in the low frequencies whereas the intelligence is modulated in the higher frequencies. The normal power level of the voice is about 100 db. below 1 watt/ square centimeter, with a variation of plus or minus 10 db. between the strong and weak talkers. Converted into electrical energy by standard microphones, these levels correspond to normal line levels of about -4 dbm. with a spread of plus or minus 3 db. between strong and weak talkers. Peaks of the order of 8 to 10 db. above the norm may be caused by broad vowel sounds which have high power content. A voice to noise ratio of 6 db. is the minimum ratio for marginal intelligibility and 13 db. should be the minimum allowable for engineering purposes.
Manual telegraphy	Spectrum: 0-50 cps. Telegraphy is a direct current signalling system wherein the current is interrupted in conformity to an intelligence code. The transient harmonics generated by the keying are a function of the keying speed. If tone modulation is used, the spectrum is that of the tone, plus and minus the keying spectrum. The average telegrapher can achieve a speed of as much as 25 or 30 net words per minute for short periods, though 15 - 20 net words per minute is the usual average for long periods. (Net words per minute is based on words of text per minute of circuit time. The time consumed

in headings, addresses, and operating instructions is charged as circuit time.) However, manual telegraphy has the advantage of being able to operate under marginal conditions when all other systems are blanked out by noise.

Automatic telegraphy

Spectrum: 0-300 cps. High speed Morse code sent from prepared tapes and recorded automatically on inked tapes. Provides a positive record of traffic, eliminating the psychological effects on the receiving operator. Operates at high speed (300-400 net words per minute). Experienced personnel still required for operation of equipment and transcription of messages from receiving tape.

Teleprinter

Spectrum: 0-23 cps. Keyboard printing operations are converted into direct current telegraphic code signals for transmission on wire or radio links. Keyboard operations can also be made to prepare tape for automatic sending, or operate other machines to print message in page or tape form. Has advantage over other forms of telegraphy in that transcription from code is done automatically by the machine and no experienced personnel are required to transcribe text. Inexperienced personnel can achieve speeds of 20-25 net words per minute in keyboard sending while tape sending is at a standard speed of about 50 net words per minute. (60 words per minute sending speed.)

Facsimile Black & White

Spectrum: 0-500 cps. (dependent upon definition). Will transmit printed page copy or line drawings. Scanning of copy determines whether black or white signal is to be sent and systems operates in an on-off manner. Speeds of as high as 300 words per minute may be obtained when sending from the best copy (clean black print) and photographic methods of recording are used.

Ordinary speed from typewritten copy and direct recording is nearer 50 net words per minute. One disadvantage of facsimile is that the quality of received copy cannot be regenerated at relay points except by preparing new originals. On the other hand, facsimile records the actual received signal permitting reconstruction of text destroyed by noise. This differs from teleprinter which makes an interpretive decision as to the incoming signal and then prints a character. The teleprinter cannot discriminate except against impossible code combinations. If noise alters the apparent code, the teleprinter will print what it thinks it receives, not that which is actually received. Because of this factor, facsimile can operate under more adverse noise conditions than teleprinter.

Facsimile Half tone — Spectrum: 9-2000 cps. Transmission requirements are much more stringent for half tone printing than for any other type of communication circuit. Line levels must be kept within 1 db. during transmission and delay distortion must be less than 3 milliseconds. Variations in line level will change the picture contrast and change the level of black and white. Variation in delay will cause the formation of "ghosts" and shadows.

Television — Spectrum: 0-4,000,000 cps. (Dependent upon definition). Television is essentially high speed facsimile using transient recording on a cathode ray tube, enabling it to transmit moving scenes. The value of television as a pure communication system is problematical because, for just communication work, it does nothing that other systems don't do better. It may have limited usefulness in intelligence communications and for broadcasting fast moving operations (such as a CIC plot in combat operations.) The

extremely high quality circuits required for television do not give returns commensurate with energy and equipment required.

Modulation

Amplitude modulation.	The amplitude of the emitted carrier is varied in accordance with the modulator signal. Maximum modulation amplitude is equal to the carrier amplitude which makes the circuit net loss variable with distance. The sideband energy is supplied by the modulator system and amounts to 25% of the carrier power at 100% modulation. For given tube size, the carrier power, when unmodulated, must not be more than 80% of power capabilities of tubes. Noise has a predominately amplitude characteristic so that amplitude modulation systems are inherently unable to discriminate against noise.
Frequency modulation.	The frequency of the carrier is shifted in accordance with the modulated intelligence. The amplitude of the carrier is not altered except as incident to the frequency modulation process. Full modulation is an arbitrary design definition dependent upon system requirements, and may be sent at any level. Overmodulation has no meaning except as a design definition. Modulation level is independent of carrier amplitude and thus independent of radio path. Modulator need supply no power to the side bands for side band power is derived at the expense of the carrier power. The output tubes in an FM transmitter thus may be operated always at full output power rating. By limiter action in the receiver, FM discriminates against noise.

Phase modulation.

There is no significant difference between FM and phase modulation in operational aspects. The main differences are of technical significance only.

Pulse modulation.

Pulse modulation is essentially a form of amplitude modulation since the carrier is first pulse modulated and then the pulses are themselves modulated in accordance with the modulator intelligence. Since the receiving equipment is sensitive only to the particular modulation on the pulse, and not to the modulation of the carrier itself, it is insensitive to the various types of distortion which affect the carrier. Pulse modulation can be achieved in four ways.

1. amplitude-amplitude of pulse varied as in ordinary carrier amplitude modulation.
2. time - position of pulse in time is varied about the average or mean position. Is like phase modulation.
3. width - the duration of the pulse is varied with modulation.
4. Numbers - the number of pulses which occur in a unit interval of time is varied with modulation.

The chief advantages of pulse modulation are (1) the high peak power level possible in pulse technique, (2) possibilities of clipping to eliminate noise, (3) multiplexing by time sharing of carrier since no channel needs the carrier longer than for its pulse to be registered. The band width of the system varies inversely with the pulse length and for a 1 microsecond pulse is about 2 megacycles. At the present state of the art, directive arrays are necessary to concentrate the power towards the

receiver. For this reason pulse modulation systems are not suited to naval communications.

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